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AN OCEANOGRAPHIC STUDY OF THE GULF OF TEHUANTEPEC

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AN OCEANOGRAPHIC STUDY OF THE GULF OF TEHUANTEPEC

by

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AN OCEANOGRAPHIC STUDY OF THE OF TEHUANTEPEC[1]

By Maurice Blackburn

ABSTRACT

The results of four cruises to the Gulf of Tehuantepec show that chemical enrichment and biological production in near-surface waters result from the effect of transisthmian northerly winds in (a) setting up a circulation of water which results in a domed or ridged discontinuity layer and (b) stirring the upper part of that layer in the region where it is closest to the surface. The wind-induced circulation also acts on the zooplankton produced, sometimes dispersing it downstream from the enriched area and sometimes concentrating it in a clockwise eddy to the west of the ridge.

INTRODUCTION

The Gulf of Tehuantepec is a bight which forms the southern boundary of the Isthmus of Tehuantepec in southeastern Mexico. It is the southernmost major geographic feature of the Mexican Pacific coast, the last one to be passed by coastal ships before they reach the coast of Guatemala.

The first attempt to make an organized oceanographic survey in the Gulf of Tehuantepec was in December 1955, during the Expedition EASTROPIC. The survey was brief, partly because of bad weather. However, the results assembled and interpreted by Brandhorst (1958), together with information from average charts, suggested a pattern of wind-connected seasonal changes in the waters of the Gulf that could be checked by further oceanographic surveys.[2]

Six surveys of the Gulf were then made on four cruises by investigators of the Tuna Oceanography Research program of the Scripps Institution of Oceanography. The cruises were: TO-58-1 (Expedition SCOT) in April, May, and June 1958; TO-58-2 in November and December 1958; TO-59-1 in January and February 1959; and TO-59-2 in August and September 1959. There was one survey on the first cruise, two on the second, two on the third (incomplete, because of bad weather), and one on the fourth.

The purpose of this paper is to present and discuss the results of these surveys, together with information about the Gulf of Tehuantepec from other sources, as a contribution to the oceanography of the eastern tropical Pacific.

The work was made possible by financial support from the U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries. The Inter-American Tropical Tuna Commission helped to staff cruises, and the late Townsend Cromwell, of the Commission, gave much valuable advice about the planning of the investigation. The research vessels were the *Spencer F. Baird* (TO-58-1, TO-58-2), *Stranger* (TO-59-1), and *Hugh M. Smith* (TO-59-2). The paper was read by or discussed with the following persons who made

[1] Contribution from the Scripps Institution of Oceanography.

[2] A different attack upon this problem, by statistical analysis of surface temperature and wind speed data averaged for 2-degree rectangles and 10-day periods for the years 1949 through 1957, has been made by Roden (1961). This work formed part of the same research program as the present paper.

suggestions for which the writer is grateful: Robert S. Arthur, John A. Knauss, Joseph L. Reid, Gunnar I. Roden, and Warren S. Wooster of the Scripps Institution of Oceanography; Richard A. Barkley, Gerald V. Howard, J. F. T. Saur, and Oscar E. Sette of the Bureau of Commercial Fisheries; and John Lyman of the National Science Foundation.

Most of the oceanographic data used in the paper have been listed and explained elsewhere in papers containing descriptions of equipment and methods (Holmes and Blackburn, 1960; Blackburn, Griffiths, Holmes, and Thomas[3].

Sections showing vertical distributions of physical and chemical properties were prepared from station property curves drawn by the Data Processing Section of the Scripps Institution according to the method of Klein[4], from bathythermograms, and from curves of phosphate concentration against depth. The depths corresponding to preselected property levels were read from the curves. An attempt was made to secure consistency between the upper parts of sections and charts showing horizontal distributions of properties at or near the surface. The surface level was the most convenient for charts of physical and chemical properties except phosphate concentration, for which the 30-m. level was chosen in order to present contrasts. The reference level selected for dynamic height anomalies was 500 decibars, because any lower level would have eliminated too many stations. Zooplankton data are displacement volumes of small organisms (< 5 cm. long) in day or night oblique hauls made at about 2 knots through the uppermost 200-400 m.; micronekton[5] data are displacement volumes of organisms in night oblique hauls made at about 5 knots through the uppermost 90 m. (approximately); surface chlorophyll a measurements were made in the daytime, generally at local noon; and surface productivity estimates were obtained by the C-14 method by incubating the inoculated water samples in sunlit sea surface water for half a solar day.[6]

TOPOGRAPHY AND CLIMATOLOGY OF THE TEHUANTEPEC REGION

The Gulf of Tehuantepec is a large bight that lies between Port Angeles and Suchiate Bar, on the Pacific coast of Mexico adjacent to Guatemala (fig. 1). The head of the Gulf is only about 120 miles south of the southern shore of the Gulf of Mexico. On this narrow isthmus the mountain chain of the American continent becomes lower, and there is a pass (Chivela Pass, 735 feet above mean sea level) through which a survey for an interoceanic ship canal has been made. A railroad and a telegraph line cross the isthmus through this pass from Salina Cruz to Coatzacoalcos.

For the purpose of this paper the region is defined to include all waters north of latitude 13° N. between longitude 98° and 92° W. The 95° meridian crosses the Isthmus of Tehuantepec a few miles east of the port of Salina Cruz through Chivela Pass.

There is practically no Continental Shelf west of the 96° meridian, but there is a broad one east of 95° where most of the northeastern

---

[3] Blackburn, M., R. C. Griffiths, R. W. Holmes, and W. H. Thomas. MS. Physical, chemical and biological observations in the eastern tropical Pacific Ocean: three cruises to the Gulf of Tehuantepec, 1958-1959. U. S. Fish and Wildlife Service, Special Scientific Report--Fisheries.

[4] Klein, H. T., MS. A new technique for processing physical oceanographic data. Scripps Institution of Oceanography, La Jolla, Calif.

[5] Micronekton, a term occasionally found in marine biological literature (e.g., Marshall 1954), is here defined as the assemblage of actively swimming fishes, cephalopods, and crustaceans ranging from about 1 cm. to 10 cm. in length. It was collected in a net 19 ft. long, with mouth-aperature 5 ft. x 5 ft., of Marion Textiles pattern 467 nylon throughout (mesh size about 5.5 mm. x 2.5 mm.), and filtering area 7.6 times aperture area.

Footnote 5--Cont.

The displacement volumes given in the illustrations are the actual volumes of animals caught (excluding coelenterates, tunicates, and heteropods) per estimated 1,000 $m.^3$ of water strained; the estimate of water strained is the product of mouth-aperture in $m.^2$ and length of track in m., multiplied by a filtration coefficient of 0.757 which was obtained in an experiment in which flowmeter readings were compared in identical tows with and without the net. The method of hauling is given in the manuscript by Blackburn, Griffiths, Holmes, and Thomas (see footnote 3).

[6] The method of incubation was changed from time to time. At some stations, bottles were suspended from a drifting buoy in the ocean at the place where the water samples were collected (in situ method); another method was to tow bottles astern (trailing bottle method); and another was to place them in a sunlit shipboard tank of circulating surface seawater (deck incubator method). Details are given in the manuscript by Blackburn, Griffiths, Holmes, and Thomas (see footnote 3).

Figure 1.--General topography of the Isthmus of Tehuantepec.

part of the Gulf is less than 200 fathoms deep.[7]

Detailed climatic information is available for the Gulf itself in the form of monthly average charts of surface wind, precipitation, cloudiness, etc. (U.S. Navy, 1955; Meteorological Office, London, 1956). Some of this information is available together with monthly average weather data for land stations on the Isthmus (U.S. Navy Hydrographic Office, 1949). The main features have been conveniently summarized in a text (U.S. Navy Hydrographic Office, 1951) from which the following are extracts.

> The rainy season extends from May to November and the balance of the year constitutes the dry season . . . at Salina Cruz (the annual fall) is 39 inches . . . .
>
> Along the lower Mexican coast the prevailing direction of the trades is northwesterly, tending to parallel the coastline . . . .

[7] Sea-bottom topography is shown in Topographic Chart No. 9 prepared by the Bureau of Commercial Fisheries and the University of California, Institute of Marine Resources, issued on December 27, 1960 by the Bureau of Commercial Fisheries.

During the cool season the Gulf of Mexico, the southwestern part of the Caribbean Sea, the Gulf of Tehuantepec on the Pacific side of southern Mexico, and western coastal waters of Costa Rica, are more or less subject to northerly winds which occur as a result of the southward extension into the Gulf of Mexico of strong anticyclones from the Plains States .... Northers usually have their greatest strength and frequency during the periods from November to February, inclusive, but conditions favorable to their development may occur as early in the season as October and as late as April.

The northerly gales of the cooler months which occur in the Gulf of Tehuantepec are known as Tehuantepecers. The Tehuantepecer results from the anticyclone to the northward. It is frequently, in fact commonly, a wind of greater force than the norther of the Gulf of Mexico which feeds it .... Its cause is a strong flowing of anticyclonic air through the comparatively low and narrow Tehuantepec Pass, from which it emerges upon the Pacific slope. It then pours violently down to the Gulf of Tehuantepec, and frequently overspreads the entire Gulf. It often continues at sea far southward ....

The wind direction may be from west-northwest to east, with northwest to northeast as the most common directions ....

At Salina Cruz the north-northeast wind throughout the year averages force 6, and the north wind averages between forces 4 and 5....

Figure 2A represents average surface wind roses for different periods of the year for an ocean area centered at 14° N., 96° W., adapted from monthly charts (U.S. Navy, 1955). More winds are observed from the north than from any other direction throughout the year, especially from October through April; the only other winds of any consequence during this period are from the northeast, northwest, and west, the last becoming more frequent in the spring months; the average velocity of north wind is over 16 miles per hour (i.e., over Beaufort force 4) from October through January and over 10 miles per hour (i.e., over Beaufort force 3) from February through April. The period June through August is characterized by light or gentle winds from the north, northeast, and east. May and September are months of variable winds, light or gentle on the average. Southerlies are infrequent at all seasons.

PREVIOUS OCEANOGRAPHIC INFORMATION

Mean surface temperature

The Gulf of Tehuantepec is in the thermal-equatorial region of the eastern Pacific, which

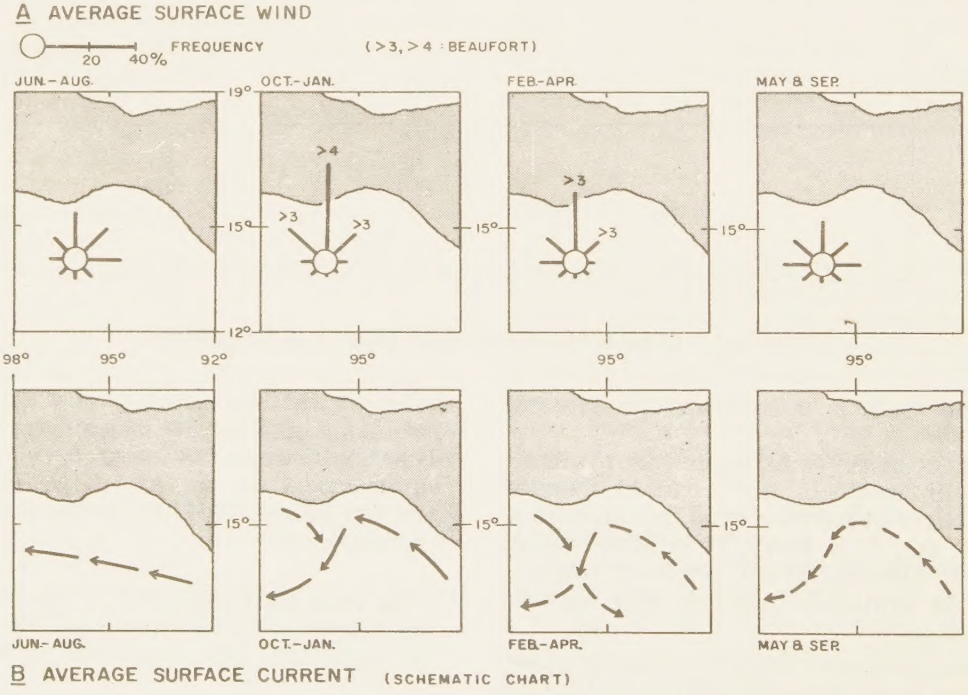


Figure 2.--Average surface wind and surface current in the Gulf of Tehuantepec: current diagrams schematic; broken and unbroken arrows indicate, respectively, currents less than and more than 10 miles per day.

extends approximately from latitude 10° N. to 20° N. along the coast in most months. In the period October through February the surface water in the Gulf is at least 1° C. colder than that in immediately adjacent parts of the ocean. The area of cold water extends up to 400 miles in a south-southwesterly direction from the head of the Gulf of Tehuantepec, whereby there is more cool surface water in the western half of the Gulf than in the eastern half. Details are available in published average monthly charts (U.S. Navy Hydrographic Office, 1944; Meteorological Office, London, 1956).

Mean surface current

Cromwell and Bennett (1959) presented charts of the main features of surface circulation (average surface current set reported by ships) in the eastern tropical Pacific in each calendar month. An inspection of the information for the Gulf of Tehuantepec showed four main patterns of circulation, characteristic of the following periods: June through August, October through January, February through April, and May and September. These patterns are shown schematically in figure 2B: unbroken arrows indicate stronger current (at least 10 miles per day) and the broken arrows indicate weaker current.

The simplest pattern is the summer one which shows a simple drift west-northwestward through the Gulf. With the beginning of persistent northerly winds in October this current receives a strong contribution from the north and the main line of flow becomes sinuous; there is a weaker contribution from the northwest which indicates possible continuity of drift (a clockwise eddy) in the western part of the region, and this is shown in the January chart of Cromwell and Bennett (1959). In the period February through April the northwest contribution becomes more important than the northern, and there is some development not only of the above-mentioned clockwise eddy in the western half of the region but also of an anticlockwise eddy in the eastern half. May and September are months of transition to and from the summer circulation pattern; the data are consistent with a sinuous line of weak flow from east to west.

Transitory eddies, clockwise in the west of the Gulf and anticlockwise in the east, seem to occur rather regularly in association with northerly winds, to judge from the following remarks on inshore currents (U.S. Navy Hydrographic Office, 1951):

> During northers the current sets strongly to the northward and eastward along the shore on the western side of the Gulf, and to the northward and westward inshore on the east side of the Gulf; at other times the current sets in the opposite direction. This confusion of currents may be accounted for in this way: the fury of the norther blows the water out of the Gulf to the southward and, as the waters lower at the head, there is a rush along each shore to the northward to supply or fill the vacancy. When the norther moderates or ceases to blow, the water that was banked up, as it were, flows back into the Gulf, and the extra amount rushes out along each shore to the southward.

Mean depth of mixed layer

According to the quarterly charts of thermocline topography of the eastern tropical Pacific by Cromwell (1958), the mixed layer in the Gulf of Tehuantepec has an average depth of between 10 and 30 m. except in the quarter October-December, when it is less than 10 m. There were, however, very few observations available from the Gulf region. The charts were based on all available bathythermograms filed at the Scripps Institution of Oceanography.

Mean standing crop of zooplankton

Brandhorst (1958) presented a contour chart of average zooplankton standing crop for the quarter October-December, based on data from expeditions made in 1955 and 1956. It indicates that the Gulf of Tehuantepec is a region of fairly high standing crop of zooplankton at this season (200-400 ml./1,000 $m.^3$, twice as much as in adjacent coastal waters), but is based on very few observations in that area.

Data from Expedition EASTROPIC

Sections and charts by Brandhorst (1958) summarize the physical and chemical information gathered at the seven stations (*Spencer F. Baird* stations 80-86) occupied in this region in early December 1955. A Tehuantepecer occurred during the survey. Sections of temperature, salinity, thermosteric anomaly, and dissolved oxygen concentration are all similar: they show the discontinuity layer rising away from the coast to a depth of about 10 m. below the surface at 15° 10' N., 95°29' W. (station 83) and then falling to about 50 m. below the surface in the southwestern part of the Gulf region. Brandhorst called this topography a "dome," a term introduced into oceanography by Cromwell (1958) to describe a similar feature off the Costa Rican coast, and noted its resemblance to the Costa Rican

dome. A chart of the dynamic topography located the top of the dome at about 15° N., 95° W., but the area of coolest surface water was somewhat southwest of this; measurements of surface current by geomagnetic electrokinetograph (GEK) were consistent with the dynamic topography.

Brandhorst (1958) concluded: From the figures it can be deduced that this "dome" is associated with strong current, circling counterclockwise in the Gulf. It is remarkable that the cool surface water does not coincide with the center of the dome.

OBSERVATIONS ON CRUISE TO-58-1, EXPEDITION SCOT (MAY AND JUNE 1958)

The Gulf of Tehuantepec was surveyed from May 27 through June 2, 1958. Figure 3 shows the ship's track, observation points, and section lines. The weather was generally fine, the wind mainly from the north and northwest and light, except at station 82 where a northerly at Beaufort force 5 was encountered on May 29.

To facilitate comparison of charts and sections for this and the other cruises, it should be noted that bathythermograph (BT) observations between stations are numbered where necessary as x - y where x is the number of the last station and y indicates the order of the observation in the series made between stations x and x + 1: e.g., 81-2, the second BT after station 81; 0-13, the thirteenth BT between the beginning of the cruise and station 1.

Section A-A, as shown in figure 3 and on similar charts for later cruises, runs more or less parallel to the edge of the Continental Shelf, which extends further south in the eastern part of the Gulf than in the western. Section B-B is a meridional section along the axis of Chivela Pass.

Horizontal distributions of properties

The charts in figure 4 show horizontal distributions of (A) dynamic height anomalies and surface current by GEK, (B) surface temperature, (C) surface salinity, (D) surface oxygen, (E) inorganic phosphorus (phosphate) at 30 m., and (F) zooplankton and micronekton. Figure 5 gives similar data for surface chlorophyll a and productivity.

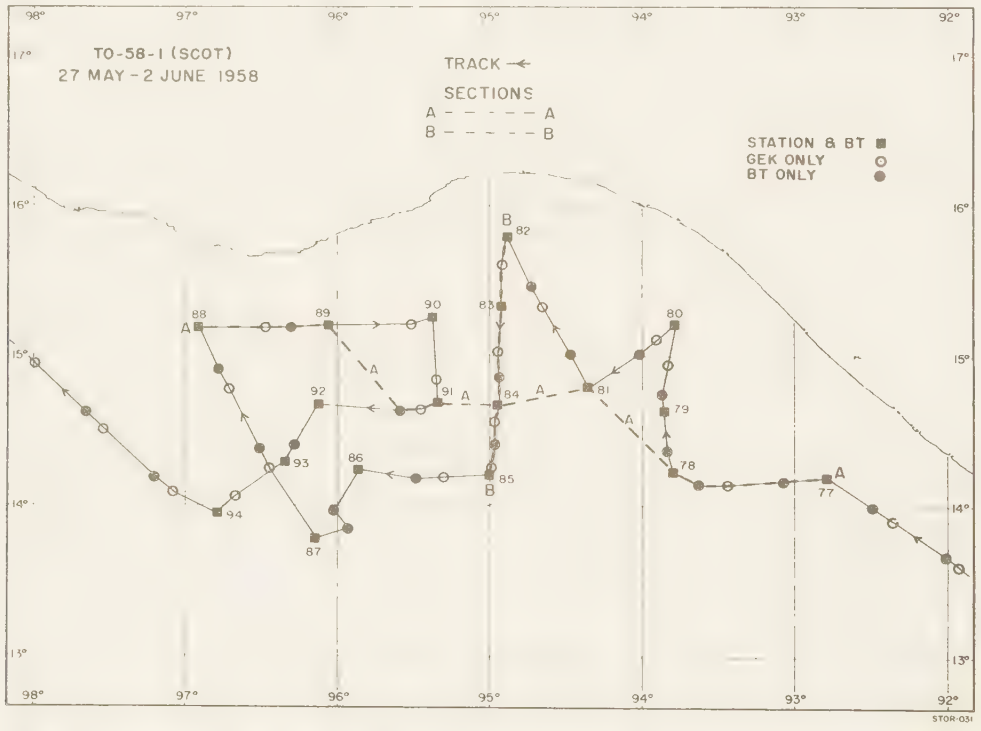


Figure 3.--Track chart of cruise TO-58-1, Expedition SCOT, in the Gulf of Tehuantepec.

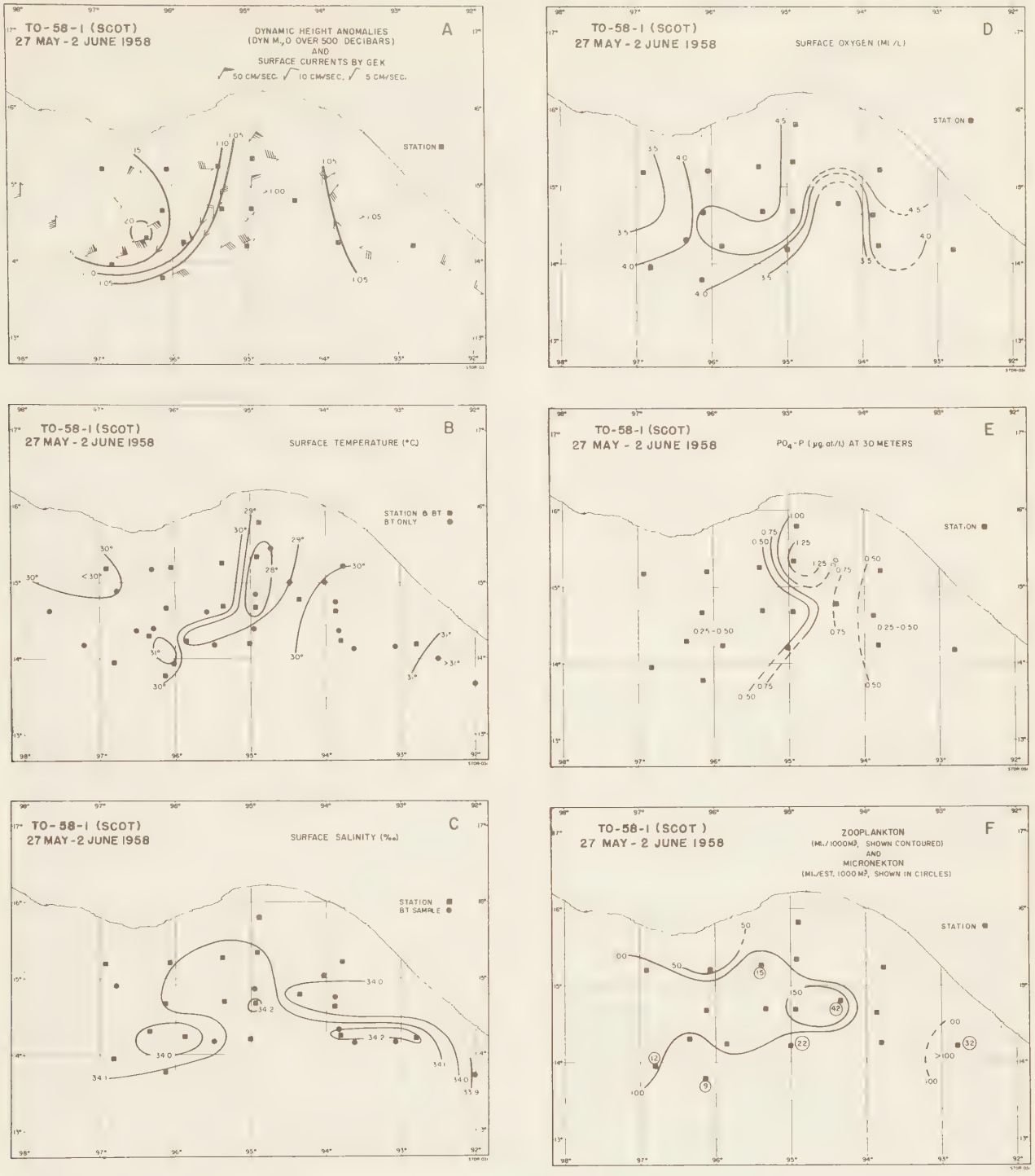


Figure 4.--Horizontal distributions of properties on cruise TO-58-1.

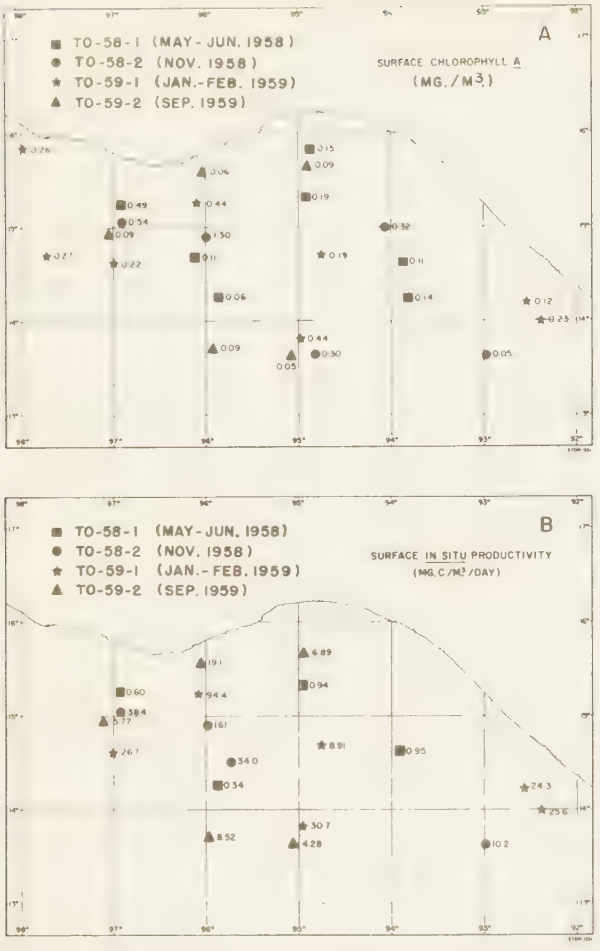


Figure 5.--Surface chlorophyll a and in situ productivity measurements from all cruises in the Gulf of Tehuantepec.

Figures 4A and 4B are consistent with the above-mentioned ideas and observations about surface current and surface temperature distribution, except that the feature called a "dome" by Brandhorst (1958) would be better called a "ridge" (Cromwell, 1958) running more or less south-southwestward from the head of the Gulf between meridians 94° and 96° W. The dynamic topography predicts a weak northwesterly current to the east of this ridge and a strong southwesterly current to the west of it. GEK observations confirm the latter, and further indicate some clockwise flow around a "hollow" (Cromwell, 1958) to the west of the ridge; they also suggest anticlockwise flow around the southern end of the ridge, accompanied by divergence of current in the vicinity of 14°10' N., 95°10' W. Surface temperatures were generally lower above this ridge than elsewhere, but lowest along its western edge (especially about 15° N., 95° W.) rather than in its center.

The higher surface salinities (>34.1‰) occurred mainly but not entirely in the ridge area (fig. 4C). Surface oxygen concentration ranged from 3.5 ml./l. at one station on the ridge to 4.5 ml./l. at several stations along its western flank (fig. 4D). Phosphate values were consistently higher over the ridge than elsewhere (fig. 4E).

The two highest measurements of zooplankton standing crop (150-200 ml./1,000 $m.^3$) were at ridge stations (fig. 4F), but it would be most correct to say that zooplankton abundance was highest on and west of the ridge, at a level about average for the eastern tropical Pacific (Holmes, 1958). No conclusion can be drawn about the distribution of micronekton (only six observations); most of the values were higher than average for the eastern tropical Pacific (Blackburn and Associates, 1962[8]). Chlorophyll a and productivity values (figs. 5A and 5B) were mainly lower than average for the eastern tropical Pacific (Holmes, 1958), and nothing definite can be said about their distribution within the Gulf region.

Surface temperatures east and west of the ridge (fig. 4B) were much higher than average for the time of year. This is a manifestation of the anomalous temperature conditions that prevailed in the eastern Pacific generally in 1958 (Rodewald, 1959).

Vertical distributions of properties

Figure 6 shows profiles of (A) temperature, (B) salinity, (C) thermosteric anomaly, (D) oxygen, and (E) phosphate, to 200 m. along the east-west section A-A (fig. 3). In this group of sections, and similar groups elsewhere in the paper, no attempt has been made to draw isopleths of salinity, thermosteric anomaly, etc. to agree with the extra detail available, from BT data, for the isotherms: that is to say, assumptions regarding the similarity of temperature distributions to other distributions have been kept to a minimum.

All these figures show: a very gradual elevation of the top of the discontinuity layer from about 92°40' to about 94°20' W., where the top of the ridge occurs at about 20 m. below the surface; further west, to about

[8] Refer to figure 12 of this paper.

95°20', a slight deepening of the top of the layer with the extension of isopleths (except for phosphate) from the top of the layer to the sea surface, with indications of a local shallow depression at 95° W. (station 84); and further west still, a steep decline of the top of the discontinuity layer to about 70 m. at 97° W., with the disappearance from the sea surface of isopleths associated with this layer.

Figure 7 shows the same properties along the north-south section B-B, i.e., approximately along the axis of the ridge and a little west of its crest. The deepening of the top of the discontinuity layer at 14°40' N. (station 84) appears more clearly as a local depression; in this area and for about 40 miles northwards the isopleths (temperature and salinity) of the layer top extend to the sea surface, which they do not at the southern end of the section and do to a much less extent at the northern (inshore) end. The oxygen distribution is not very informative in itself, but can be reconciled (with the aid of figs. 4D and 6D) with other observations. No phosphate isopleths reach the sea surface in figure 6E or figure 7E, because of the contour interval selected. There is no clear evidence of a general change in slope of isopleths at either end of section B-B.

Interpretation

At the time of the survey, the circulation in the Gulf resembled the middle schematic diagrams in figure 2B (October-January or February-April, mostly the latter), as shown by dynamic topography, isopleth slopes in sections, and GEK measurements: the western eddy was strong (1-2 knots), the eastern eddy weak or nonexistent. The effect of the circulation was to elevate the discontinuity layer into a ridge running more or less north and south from the head waters of the Gulf, with its crest about 20 m. below the surface and its western edge along meridian 95° W. (approximately).

Waters of the upper part of the discontinuity layer were mixed upwards to the surface above the ridge, but more so along the western flank of the ridge than elsewhere. This could be interpreted as a result of greater wind stress along 95° W. than further east, but if that were the complete explanation the vertical mixing should have been greater inshore than in the middle of the Gulf, whereas the reverse was the case. An area of divergence in the middle of the Gulf at about station 84 is therefore hypothesized: it could have occurred between the western clockwise and the eastern counterclockwise eddy mentioned in the preceding paragraph, although there is only slight evidence that the latter eddy existed.

Concentrations of phosphate and chlorophyll *a* were not high in surface waters, even over the ridge, nor was productivity. Zooplankton concentration was about average for the eastern tropical Pacific, and distributed in a way that suggests formation on the ridge, dispersal downstream to the southwest, and concentration in the eddy to the west of the ridge. Micronekton concentration was above average for the eastern tropical Pacific. These results could mean that the Gulf was declining, from a peak some weeks or months earlier, in its capacity to produce biota at the lower trophic levels, despite the incomplete stratification of its waters.

OBSERVATIONS ON CRUISE TO-58-2 (NOVEMBER 1958)

There were three parts of this cruise in the Gulf of Tehuantepec: part 1, November 8-9, consisted of a BT survey along 95° W. north from about 14°30' N.; part 2, November 13-16, was a BT and GEK survey as shown in figure 8A; and part 3, November 22-30, was a station, BT, and GEK survey as shown in figure 8B. The four section lines in figure 8A are comparable with those in figure 8B, and two of them (A-A, B-B) are comparable with the same section lines for the previous cruise (fig. 3).

The weather was calm on part 1 of the cruise; on part 2 it was mild, winds being mostly from north to west and not exceeding Beaufort force 3; between parts 2 and 3, on November 19 and 20, there was a northeaster with force 5 to 7, which is identifiable in the records of the Salina Cruz Meteorological Observatory and appears to have been the first strong norther for the season; on part 3 of the cruise winds were predominantly from the north and up to force 5.

Horizontal distributions of properties

Figures 9A and 9B are charts of surface current (by GEK) and surface temperature respectively, as observed on part 2 of the cruise (before the Tehuantepecer).

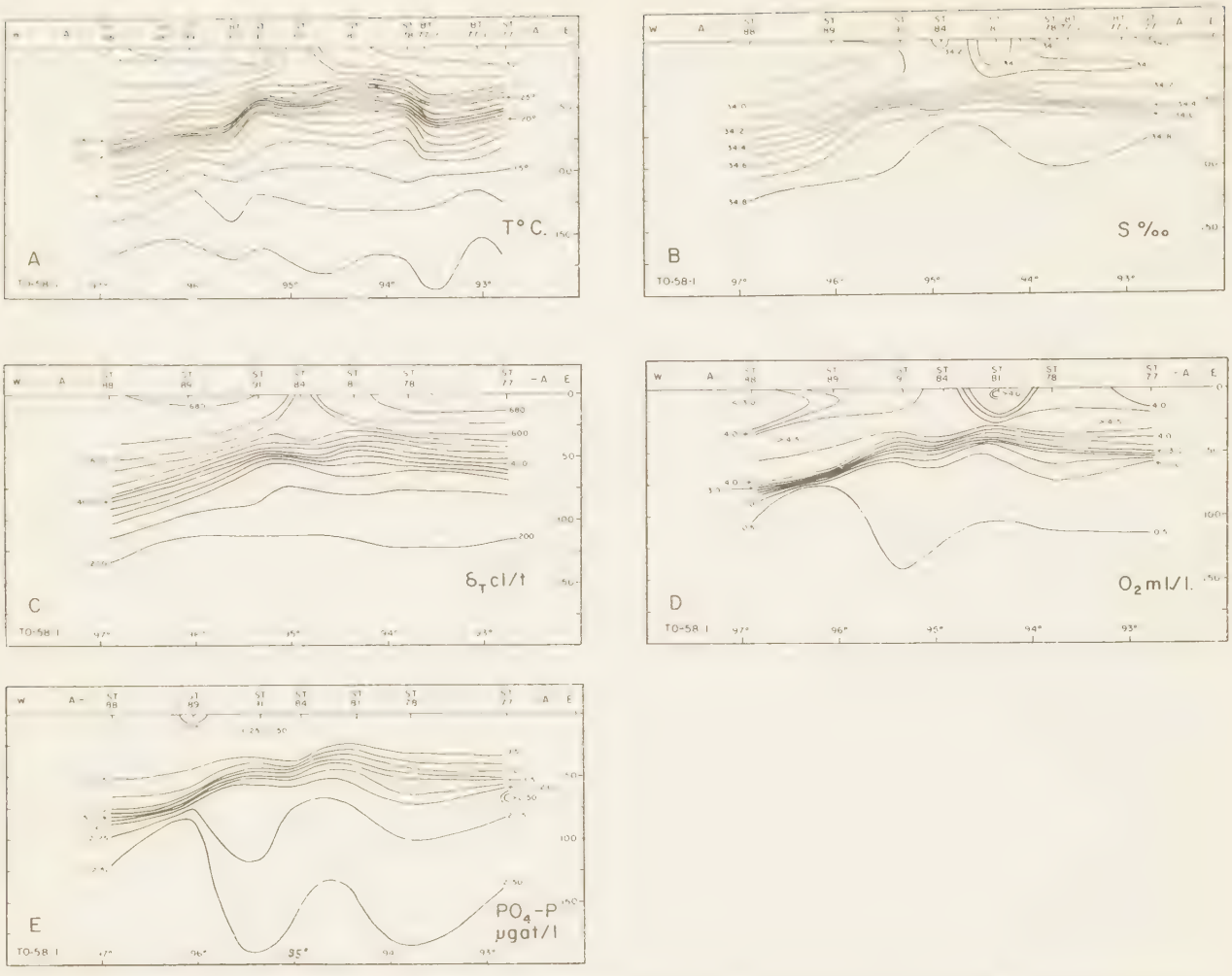


Figure 6. --Vertical distributions of properties on cruise TO-58-1 along section A-A (see fig. 3); depth scale in m.

The data in figure 9A could be interpreted to mean that dynamic height anomalies were lowest in the area between 14° and 15°N. and 95° and 96°30' W., i.e., about a degree to the west of the area of lowest dynamic height anomalies found in May and June 1958 (TO-58-1, fig. 4A).

Figure 9B which shows the north-south belt of cool surface water lying about 1 degree further west than it does in figure 4B, is consistent with figure 9A as interpreted above. Other differences between figures 9B and 4B are (a) the presence of the coldest water near the coast and (b) the fact that the cool belt runs offshore in a southeasterly direction at its southern end, in figure 9B; (b) is consistent with GEK observations south of 14° N. between meridians 96° and 95° W. (fig. 9A), which could mean anticlockwise flow around the southern end of the ridge.

Figure 10 shows the more numerous distributions available for part 3 of the cruise (after the Tehuantepecer): they are (A) dynamic height anomalies and surface current by GEK, (B) surface temperature, (C) surface salinity, (D) surface oxygen, (E) phosphate at 30 m., and (F) zooplankton. No micronekton observations are given because micronekton sampling on TO-58-2 was experimental and did not yield observations comparable with those of the other cruises. The surface chlorophyll a and productivity data are in figure 5.

Figure 10A is like figure 4A in the way it shows the north-south ridge and the high-velocity clockwise eddy to the west of it, and the GEK observations agree fairly well with those of figure 4A at the same longitudes.

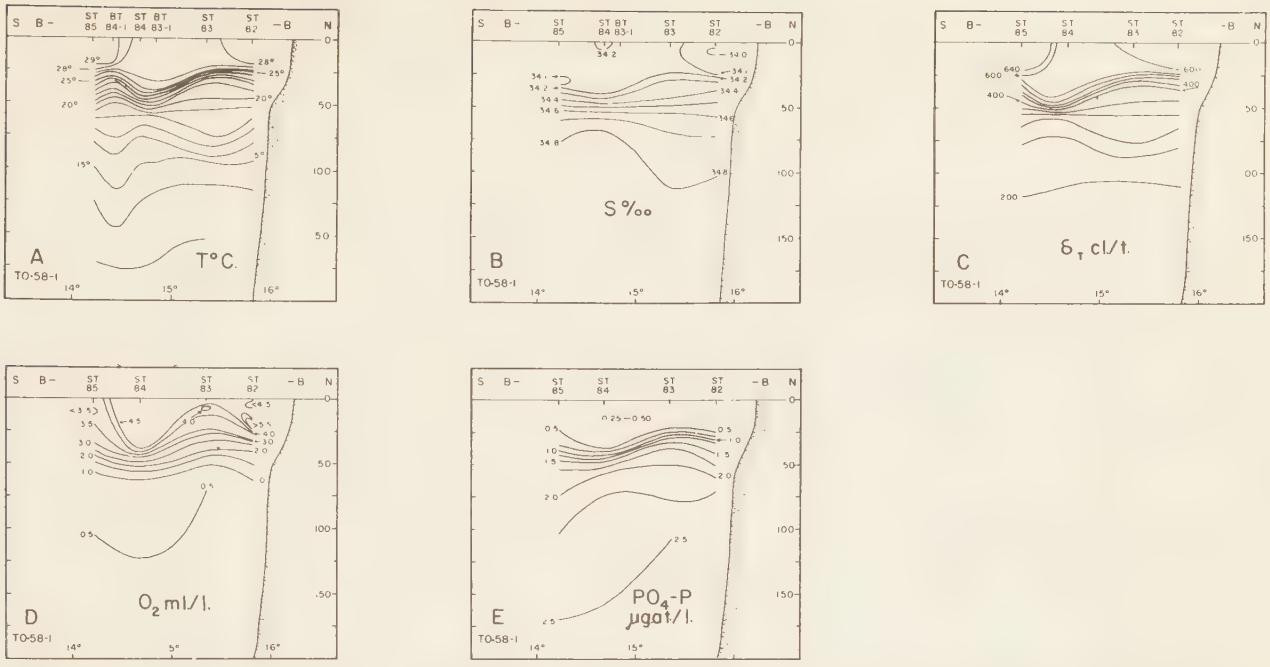


Figure 7.--Vertical distributions of properties on cruise TO-58-1 along section B-B (see fig. 3); depth scale in m.

Figure 10B shows the same meridional arrangement of most of the isotherms as observed on the previous surveys (figs. 4B and 9B), but the minimum temperature is lower and more widely distributed. Figure 10B also differs from fig. 9B in that the cold center is in mid-Gulf, as in figure 4B, not adjacent to the coast. In the Gulf as a whole, surface temperatures were higher than average for the month, indicating continuation of the anomalous temperature regime mentioned previously.

Surface salinities (fig. 10C) were lower than in May and June (cruise TO-58-1), as would be expected at the end of the rainy season. The highest salinities occurred broadly with the lowest temperatures. Surface oxygen concentrations in the same area were in the range 4-5 ml./l. (fig. 10D). Phosphate values at 30 m. were highest between 95° and 94° W. (fig. 10E).

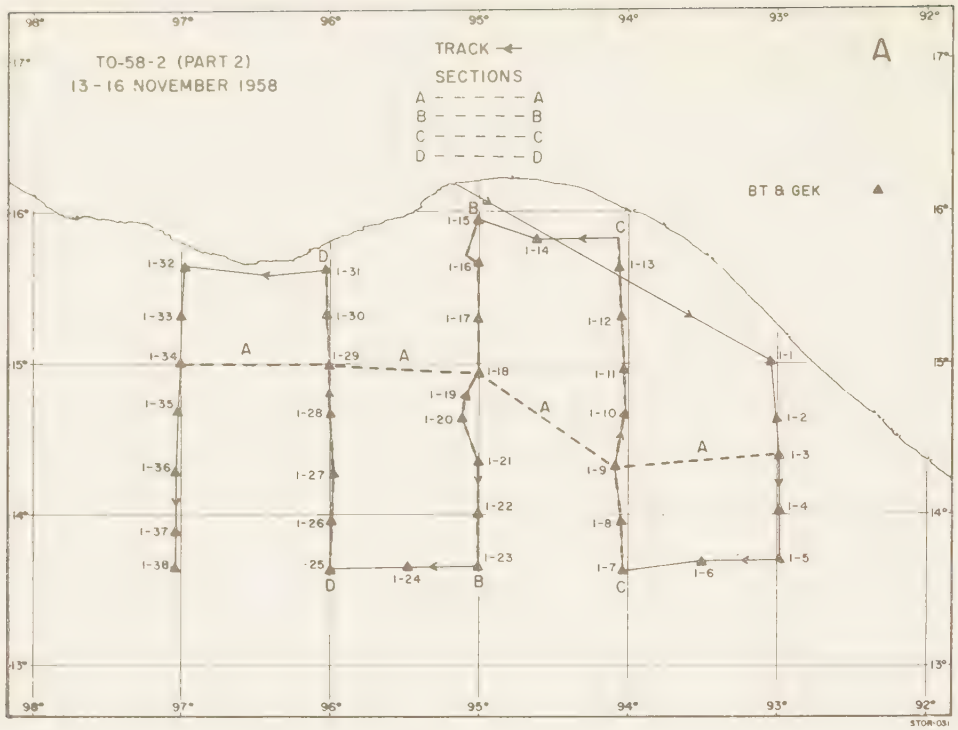
Zooplankton standing crops (fig. 10F) were highest in much the same area as in May and June (cruise TO-58-1, fig. 4F), but at a much higher level (200-600 ml./1,000 $m.^3$). Chlorophyll *a* and productivity values, the latter especially, were also higher in the main with maxima respectively 1.30 mg./$m.^3$ and 161 mg.C/$m.^3$/day (fig. 5).

These maxima occurred at station 15 (about 15° N., 96° W.) which was one of two stations where the water was very green and nets were clogged with phytoplankton; no quantitative phytoplankton observations were made at the other station (station 11, about 15° N., 95° W., in the center of the colder more saline water). Zooplankton was only moderately abundant at these two stations of rich phytoplankton. The high surface oxygen concentration at station 15 is consistent with the high productivity there.

Vertical distributions of properties

Figure 11 shows the following profiles along the east-west section A-A: (A) and (B), temperature on parts 2 and 3 of the cruise, respectively; (C-F), salinity, thermosteric anomaly, oxygen, and phosphate, all on part 3.

The comparison between the two temperature profiles indicates the effect of a Tehuantepecer and resulting current on the thermal structure of the Gulf. Before the gale the depth of the thermocline top ranged from about 25 m. at 93° W. up to 20 m. at 94° W. (the crest of the ridge) and thence down to 40 m. at 97° W.; the corresponding depths after the gale were about 40, 12, and 75 m. In each case the isotherms from the



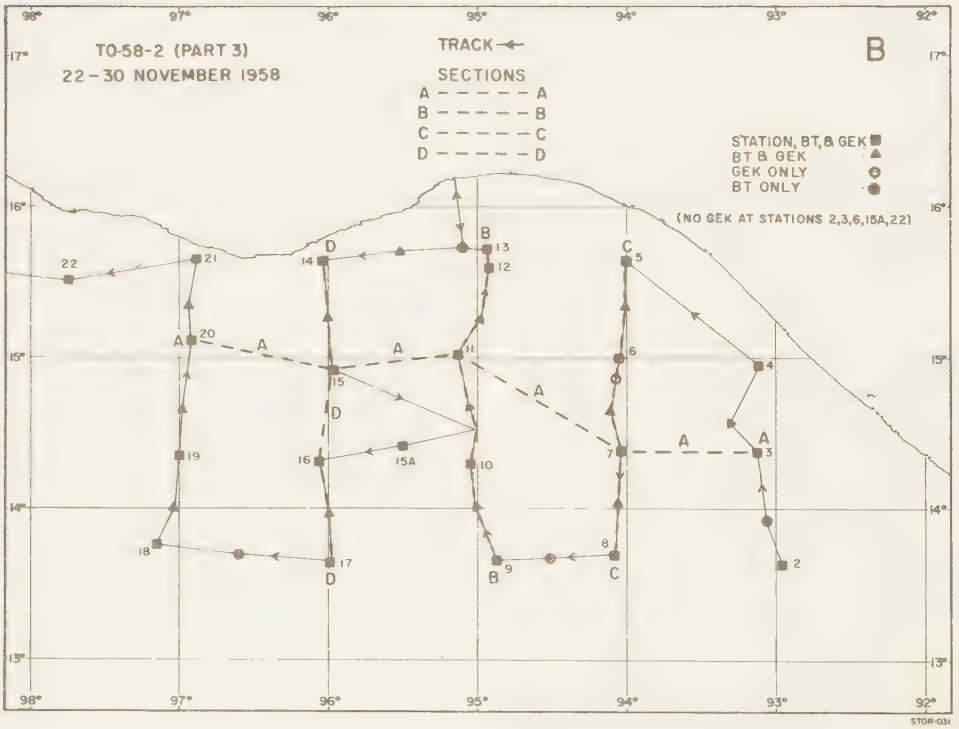


Figure 8.--Track charts of cruise TO-58-2, parts 2 and 3, in the Gulf of Tehuantepec.

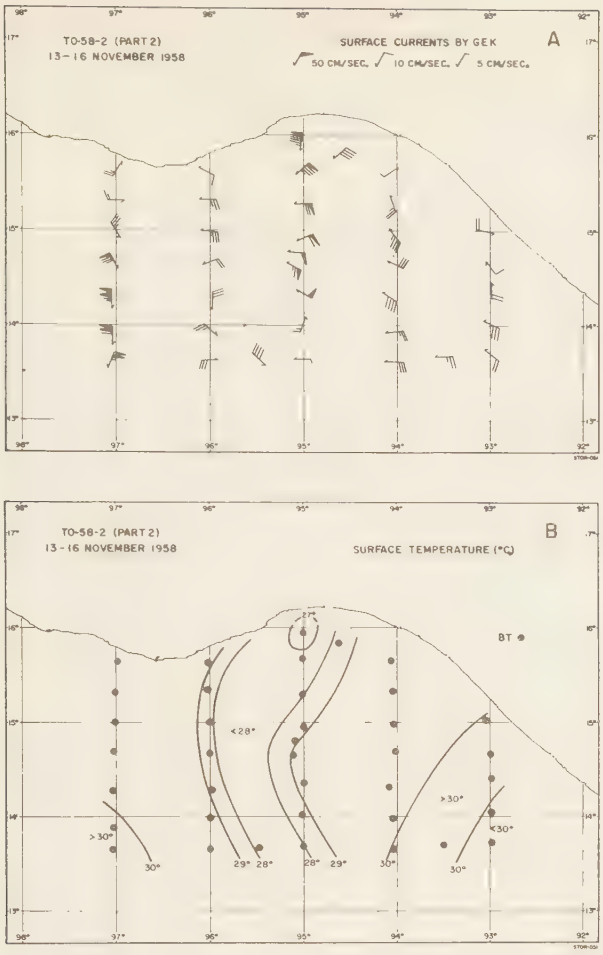


Figure 9.--Surface current (GEK) and temperature distributions on cruise TO-58-2, part 2.

thermocline top reached the surface to the west of the crest of the ridge, the coldest surface isotherms being respectively 28° and 26° before and after the gale; in the first case the lower part of the thermocline remained well-developed in the region of upward movement of cold water, but in the second case it was greatly weakened. Figures 11C, 11D, and 11F (salinity, thermosteric anomaly, and phosphate) agree with figure 11B (temperature on the same part of the cruise): the secondary (upper) halocline on the right of figure 11C probably indicates diluted water off river mouths on the east side of the Gulf; figure 11F shows water with over 0.5 μg.-at./l. of phosphate reaching the surface. Figure 11E (oxygen) is consistent with the others in respect to the discontinuity layer although not in respect to the distribution of isopleths, towards the surface; the latter could be associated with the high algal crops at stations 11 and 15.

Figure 12 shows the following profiles along the north-south section B-B: (A), (B), and (C), temperature on parts 1, 2, and 3 of the cruise, respectively; (D-G), salinity, thermosteric anomaly, oxygen, and phosphate, all on part 3.

Figure 12A provides no clear evidence of stirring of the thermocline; figure 12B shows slight stirring of the upper part of the thermocline at the inshore end of the section; and figure 12C, after the northerly gale, shows a weakening of the whole thermocline in mid-Gulf at station 11, more obviously than the same feature was shown in figure 11B. Figures 12D-12G are in agreement with figure 12C.

Figures 13A and 13B show temperature on parts 2 and 3 of the cruise along section D-D (96° W., see fig. 8). The thermoclines are deeper than the corresponding ones on section B-B a degree further east (figs. 12B and 12C), and the one in figure 13B is much deeper than the one in figure 13A. This agrees with earlier observations, section D-D being close to the hollow shown in figures 10A, 11A, and 11B.

On the other hand figures 14A and 14B, which present similar information along section C-C at 94° W., at the crest of the thermal ridge, show the thermocline generally closer to the surface on part 3 of the cruise than on part 2.

Interpretation

During part 2 of the cruise (the pre-Tehuantepecer survey with light northerlies) the circulation in the Gulf approximated a condition somewhat between the schematic diagrams for September and October-January in figure 2B; there was only partial development of the sinuous line of flow discussed in connection with figure 2B, which can be attributed to the absence or scarcity of strong northers during previous weeks. Consistently, the topography of the discontinuity layer was smoother than at the end of the Tehuantepecer season on cruise TO-58-1 although it showed the same major features--a north-south ridge with the isopleths sloping more gradually eastward than westward from a crest about 20 m. below the surface in longitude 94° W., and a hollow west of 96° W. Waters of the upper part of the layer were mixed upwards to the surface along the western flank of the

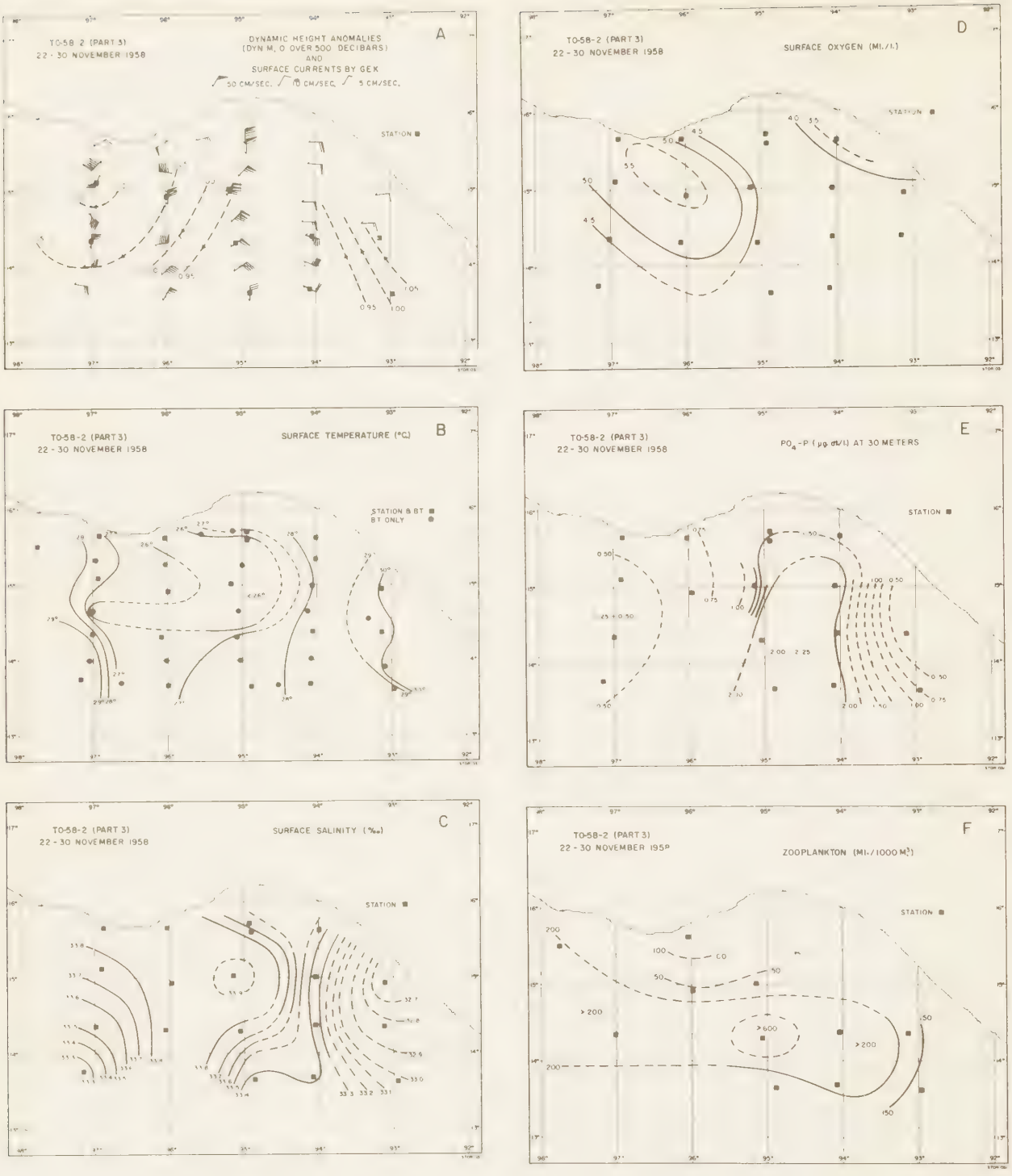


Figure 10.--Horizontal distributions of properties on cruise TO-58-2, part 3.

ridge and particularly near the head of the Gulf, where maximal wind stress would be expected; at an earlier very calm period (part 1 of the cruise) there was no sign of any such mixing anywhere along the same meridian.

On part 3 of the cruise the circulation pattern resembled that of the Tehuantepecer season (figs. 2B and 4A). The main difference from the pattern of part 2 was the strong south and southwest flow along 95°, which is attributed to the strong northerly wind that blew across the Isthmus after part 2. The topography of the discontinuity layer was altered by the circulation to make the crest of the ridge higher and its flanks lower, relative to the sea surface. The wind stirred the upper part of the discontinuity layer much more than it did before the norther, in its southerly path along the western shoulder of the ridge, bringing subsurface water upwards and greatly cooling and enriching the sea surface. As on cruise TO-58-1, in May and June, but not as on part 2 of TO-58-2, the breakdown of the layer was greatest in mid-Gulf waters (station 11), instead of inshore where wind stress should have been greatest (see Discussion). Surface temperature and salinity were respectively lowest and highest for the survey in the area of minimum stratification.

The difference in thermal structure between BT 1-18 on part 2 of the cruise and station 11 at the same position on part 3, as shown in figures 11 (A and B) and 12 (B and C), does not entirely agree with the observations of previous workers who noted the effects of real or simulated wind-stirring upon thermoclines or pycnoclines (Francis and Stommel, 1953; Cromwell and Reid, 1956; Cromwell 1960). These authors considered that the effect of an increase in wind on the thermocline is (a) to deepen it relative to the sea surface and (b) to steepen the temperature gradient in its upper part. The observations presented here, those for BT 1-18 being 4 days before a Tehuantepecer and those for station 11 being 6 days after it, show (a) but not (b); in fact they show the reverse of (b), i.e., a weakened gradient in the upper part of the thermocline; this is presumed to represent an effect of internal turbulence, possibly but not certainly connected with wind-mixing during some stage of the Tehuantepecer (cf. Cromwell, 1960, p. 77, last paragraph).

Surface and subsurface phosphate, chlorophyll a, productivity, and oxygen were greater on part 3 of TO-58-2 than on cruise TO-58-1 in May and June. A large biomass of phytoplankton was observed in the region of minimum stratification and westward, which was also in the region of maximum surface oxygen; productivity in the latter region was 161 mg.C/m.^{3}/day. Zooplankton standing crops were from two to four times as large as in May and June on cruise TO-58-1 and were concentrated in the same region, on the ridge and westward. This is again consistent with production in the eutrophic area and redistribution by the current and eddy system to the southwest and west, which doubtless played a similar role as far as phytoplankton was concerned.

OBSERVATIONS ON CRUISE TO-59-1 (JANUARY AND FEBRUARY 1959)

There were two parts of this cruise in the Gulf of Tehuantepec: part 1, January 27-31, 1959, was a station, BT, and GEK survey (fig. 15A) which was abandoned about halfway through when a Tehuantepecer caused the ship to seek shelter in Salina Cruz; part 2, February 3-7, was a BT and GEK survey commenced at the end of the gale, and virtually abandoned because of another gale which caused the ship to restrict its activities to the eastern periphery of the area (fig. 15B).

A gale was reported on January 22 before the ship's arrival in the Gulf. The weather on part 1 consisted mostly of light variable winds before station 23, and northerly winds increasing up to force 6 after that station. Part 2 of the cruise was made in calm weather through station 25, after which a northerly, up to force 6, was encountered until the ship moved east of 94° W.

Horizontal distributions of properties

Figure 16 shows the following distributions for part 1 of the cruise: (A) dynamic height anomaly, (B) surface temperature, (C) surface salinity, (D) 30 m. phosphate, and (E) zooplankton and micronekton. There is no surface oxygen chart because oxygen concentrations were not measured in surface samples.

The dynamic topography in figure 16A is recognizable as the western flank of a ridge whose crest was not, in this incomplete survey, observed over most of its area. The position in-

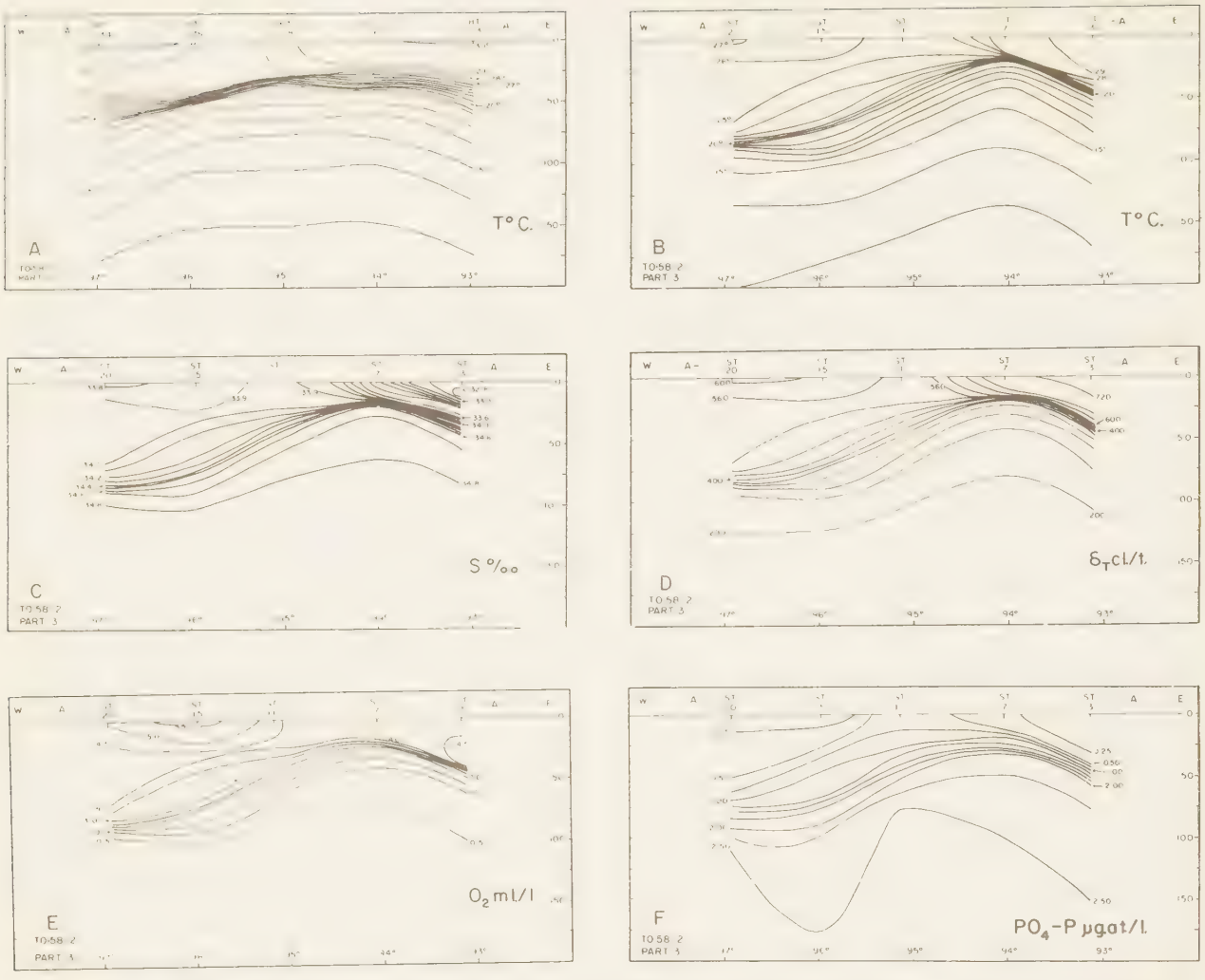


Figure 11.--Vertical distributions of properties on cruise TO-58-2, parts 2 and 3, along section A-A (see fig. 8); depth scale in m.

dicated for the northern end of the 0.95 contour is based on comparison of dynamic height anomalies at 0 over 200 decibars for station 19 and adjacent stations, because observations were made to only 200 m. at station 19. The 19 available GEK observations are not presented in this chart because it is thought that the GEK cable may have been plugged in backwards, thereby reversing polarity. The general direction of surface current indicated by these observations is northeast, which is inconsistent with the dynamic topography, but if the polarity had been reversed the direction would be southwest and in fair agreement with the dynamic topography. Moreover, comparisons between desired and attained positions of stations on this section of the cruise suggest that the ship encountered a surface current set to the west or southwest.

Figure 16B shows the familiar cool belt of surface water between meridians 95° and 96°, and an east-west arrangement of contours in the north of the area which is consistent with data for that area in figure 16A. Figure 16C shows the most saline water in the coolest area. Figure 16D shows the highest phosphate values in the ridge area, but much higher values than on previous cruises in the western part of the Gulf generally (cf. figs. 4E and 10E).

Chlorophyll a and productivity values were in general about as high as those in November (cruise TO-58-2) but higher than those in May and June (cruise TO-58-1), as shown in figures 5A and 5B. The range of zooplankton standing crop was about the same as that on TO-58-2 but the main concentration was

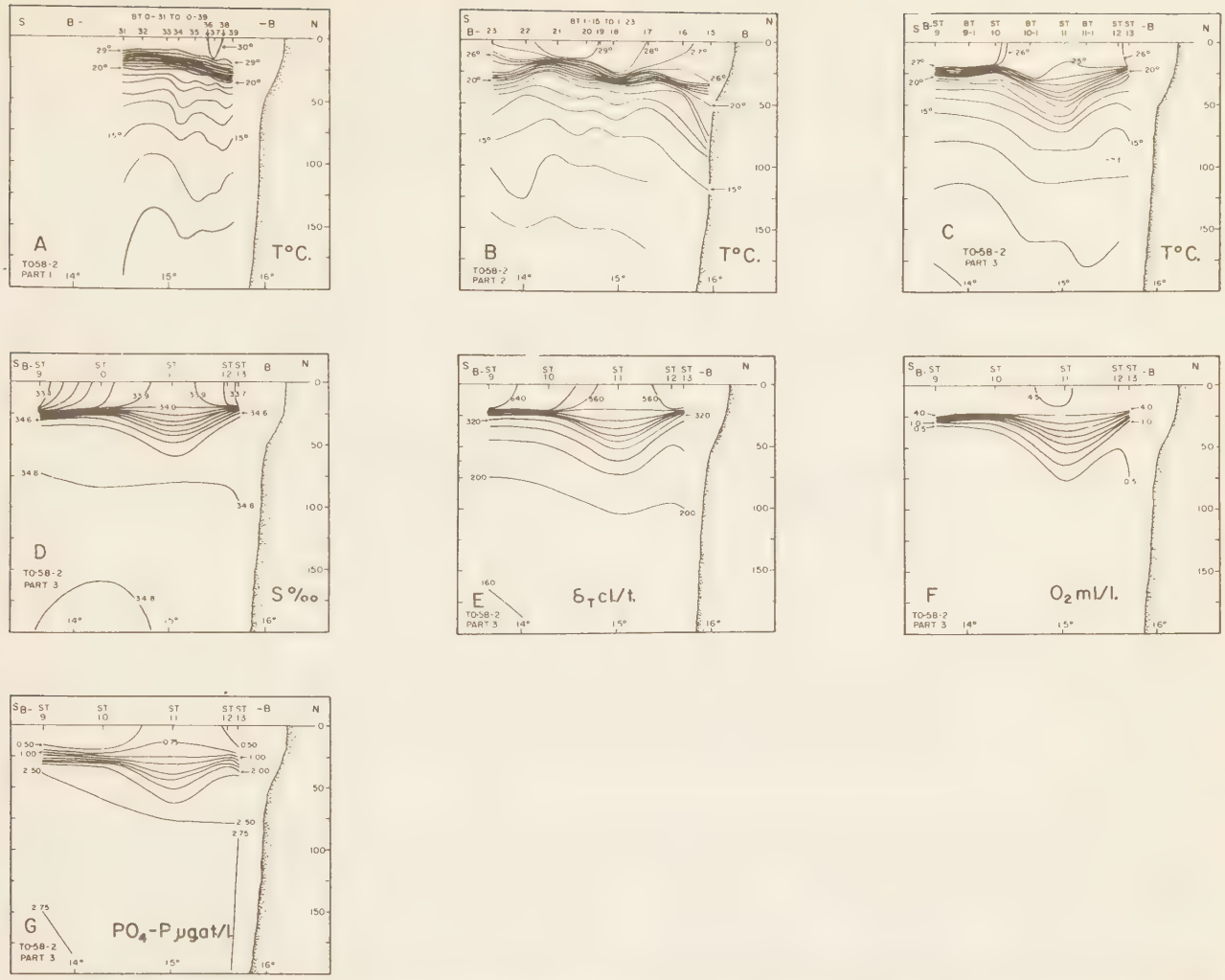


Figure 12.--Vertical distributions of properties on cruise TO-58-2, parts 1, 2, and 3, along section B-B (see fig. 8); depth scale in m.

to the west of the ridge only (fig. 16E), instead of on the ridge and westward as in figures 4F and 10F. The few available values for micronekton standing crops are of the same order as those for TO-58-1, i.e., higher than average for the eastern tropical Pacific (fig. 16E).

For part 2 of the cruise, after the Tehuantepecer, there are figures of only two horizontal distributions, surface current and surface temperature. Figure 17A shows the expected current pattern in the north and variable weak surface current in the region south of 14°40' N. between meridians 96° and 95° W. Figure 17B shows the familiar meridional arrangement of isotherms associated with north-south ridging in previous charts, and a cold center in mid-Gulf, as in figure 16B and previous charts. Figure 17B also indicates continuation of higher than average surface temperatures from TO-58-1 in May and June: it shows some water over 29° C., higher than any appearing in long-term average charts for the months of January and February.

Vertical distributions of properties

The east-west section A-A as shown in figure 15A is not quite comparable with such sections for the other cruises; it bends further south between meridians 96° and 95° and goes no farther east, because of interruption to part 1 of the cruise by bad weather. The section A-A in figure 15B is not entirely comparable either, because no observations were made west of 96° on part 2 of the cruise.

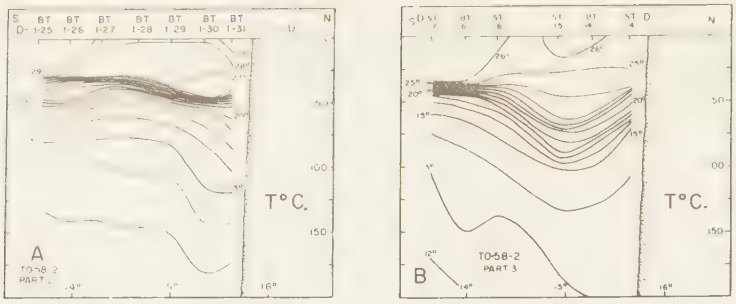


Figure 13.--Vertical distributions of temperature on cruise TO-58-2, parts 2 and 3, along section D-D (see fig. 8); depth scale in m.

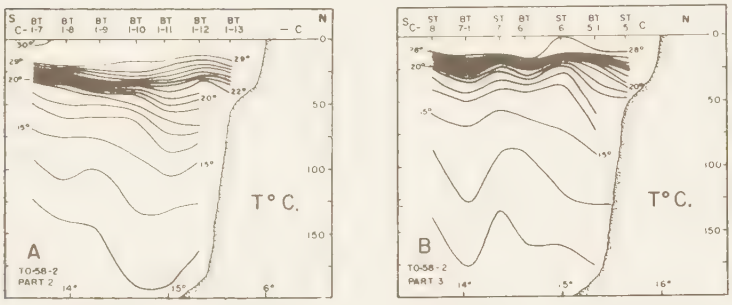


Figure 14.--Vertical distributions of temperature on cruise TO-58-2, parts 2 and 3, along section C-C (see fig. 8); depth scale in m.

Figure 18 shows the following profiles along A-A: (A) and (B), temperature on parts 1 and 2 of the cruise; (C-F), salinity, thermosteric anomaly, oxygen, and phosphate on part 1.

Figure 18A is interpreted as follows: the thermal structure below the 24° isotherm indicates the westward descent of isotherms from the ridge in conformity with the southward permanent flow, but the descent appears to be irregular because the western boundary of the ridge is sinuous (figs. 16A, 16B); the structure above the 24° isotherm results from an eastward incursion (fig. 16A) of warm water, partially destratified at about 95°30' W. under the influence of the norther that began after station 23.

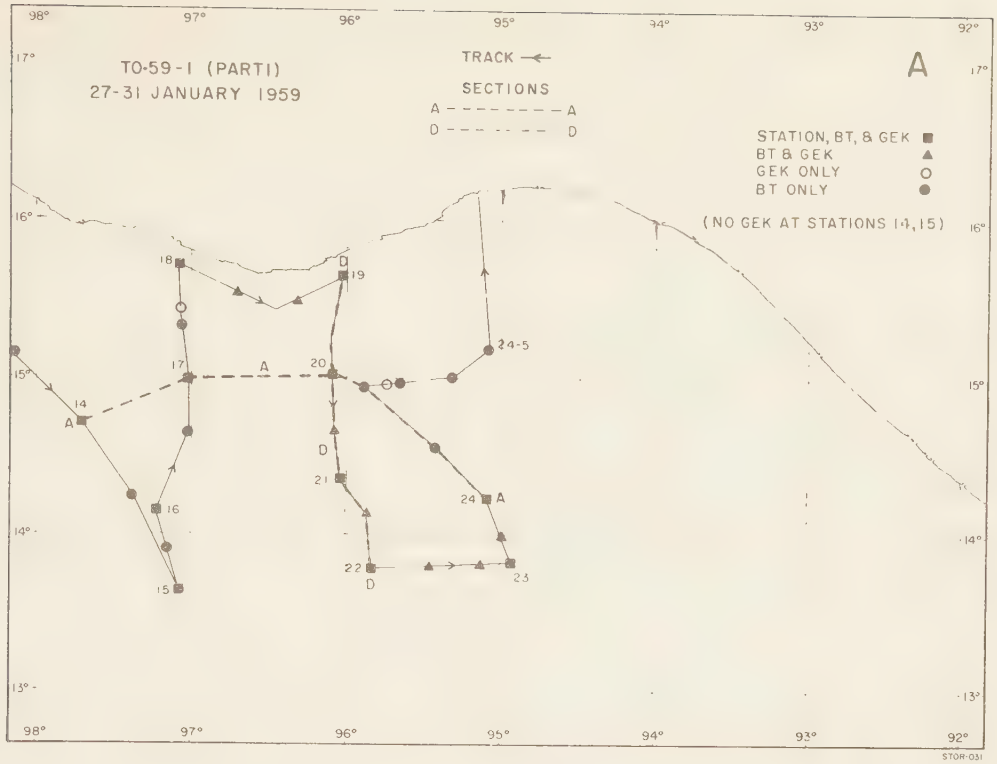
Figure 18B shows the westward descent of isotherms in the same region but without the above-mentioned complications, which were probably removed by the Tehuantepecer that occurred between parts 1 and 2 of the cruise; the double thermocline at 96° W. is explained below. The crest of the ridge is at about 94°, as in previous sections, and the area of partial vertical mixing to the west of that. The thermocline top reaches to about 15 m. below the surface, as in the post-Tehuantepecer section for November (cruise TO-58-2, fig. 11B).

The remaining parts of figure 18 agree substantially with figure 18A. Figure 18A differs from them in the part of the section between stations 20 and 24, because BT lowerings were available to provide additional temperature information.

Figure 19 shows the following profiles along the north-south section D-D (not B-B): (A) and (B), temperature on parts 1 and 2 of the cruise, (C-F), salinity, thermosteric anomaly, oxygen, and phosphate on part 1. Figure 19A is more detailed than the other profiles for part 1 because BT observations were available. In figure 19B, the lower thermocline is identifiable with that at the same latitude in figure 19A, and the upper one is believed to indicate the re-establishment of the characteristic post-norther ridging, without the sinuosity that complicated the ridge structure on part 1 of the cruise (see below). Figures 19 (C-F) agree with figure 19A.

Interpretation

Both parts of the cruise were made after Tehuantepecers, part 1 beginning about 5 days after one and part 2 about 2 days after another. It is therefore not surprising that



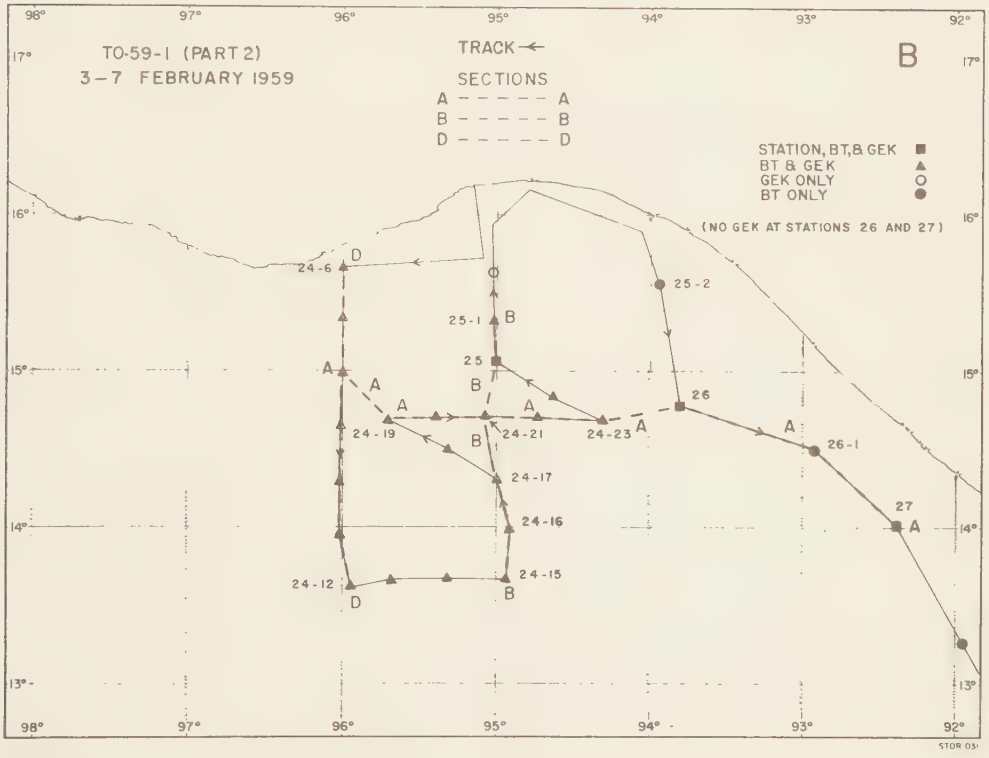


Figure 15.--Track charts of cruise TO-59-1, parts 1 and 2, in the Gulf of Tehuantepec.

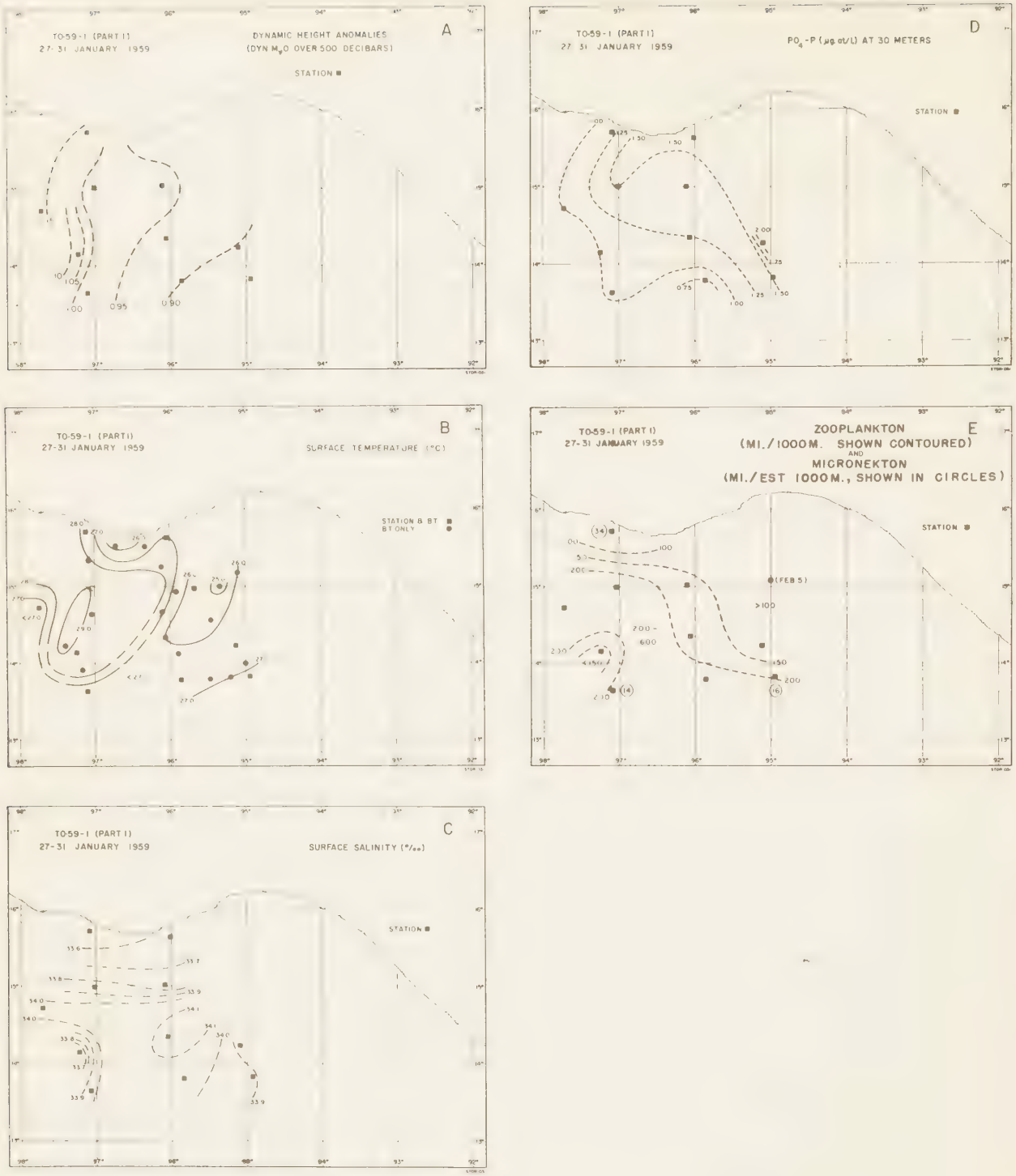


Figure 16.--Horizontal distributions of properties on cruise TO-59-1, part 1.

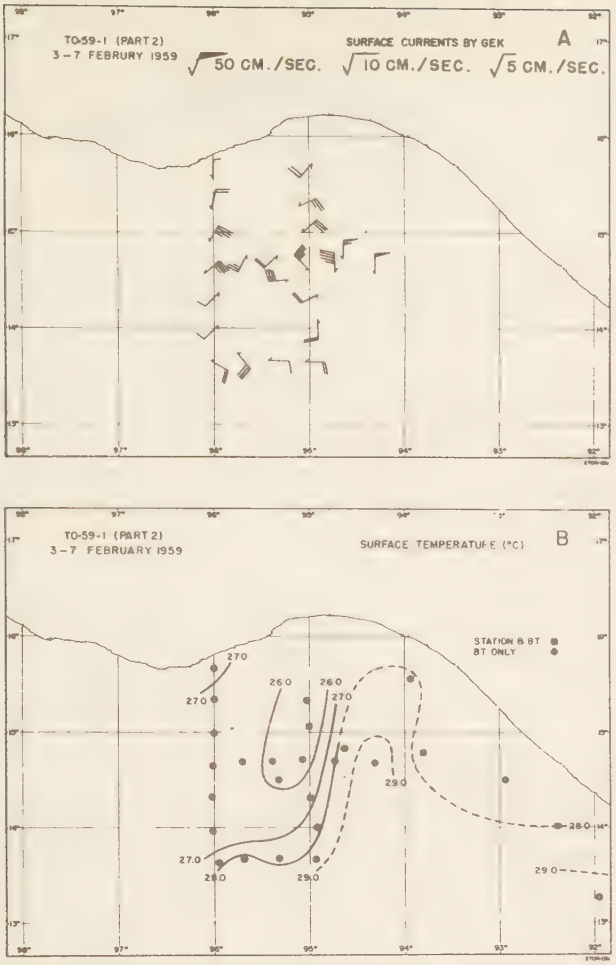


Figure 17.--Surface current (GEK) and temperature distributions on cruise TO-59-1, part 2.

the vertical and horizontal distributions observed on part 2 agreed better than those on part 1 with post-Tehuantepecer distributions observed on part 2 of cruise TO-58-2 in November. Actually the only important difference was in the sinuous western margin of the ridge on part 1 as shown by isopleths in figures 16 and 18. The surface current on part 2 of this cruise was consistent with post-Tehuantepecer conditions in the northern part of the area of observation, i.e., fairly strong towards the south and southwest; but not so in the southern part where there were indications of weaker currents in other directions. One cannot confidently interpret all these features.

The topography of the discontinuity layer on part 2 was similar to that observed in November on part 3 of cruise TO-58-2, under similar post-northerly conditions. Under such conditions the western flank of the ridge can be expected to lose any sinuosity it may previously have had, because the geostrophic current should follow the simple south or southwesterly path taken by the strong northerly. The double thermocline at about 15°, 96° W., is believed to indicate that such a change was taking place.

The upward extension of isopleths to the surface along the western edge of the ridge is indicated in about the same longitude in the charts and sections for both parts of the cruise; it occurred in mid-Gulf waters, but there are no observations to show whether or not it also occurred inshore. There was no great weakening of the discontinuity layer comparable with that at station 11 on the November cruise TO-58-2; apparently the mixing was confined to the upper part of the layer, at all places where observations were made.

The various measures of biomass and biological activity were of about the same order as those in November on part 3 of TO-58-2, although the highest values for chlorophyll a and productivity on TO-58-2 were not again observed and the area of most abundant zooplankton was more restricted.

The results of this cruise in general confirm those of the previous one in showing how winter wind-connected ocean conditions stimulate production of biota by reducing upper-ocean stratification.

OBSERVATIONS ON CRUISE TO-59-2 (SEPTEMBER 1959)

The sixth and last survey of the Gulf of Tehuantepec was made on this cruise, in the period September 6-13, 1959. It involved station, BT, and GEK observations, as shown in figure 20. It was not continued east of 94° W. because it was considered that the general situation in the Gulf was already evident from the results obtained in the area between 97° and 94° W.

Winds were mainly light and variable (predominantly easterly) before station 77, near the head of the Gulf, was reached. From station 77 to station 80, they were northerly and northeasterly at force 5, becoming weaker and more variable during the remainder of the survey. These are the conditions of a moderate but not a strong Tehuantepecer and

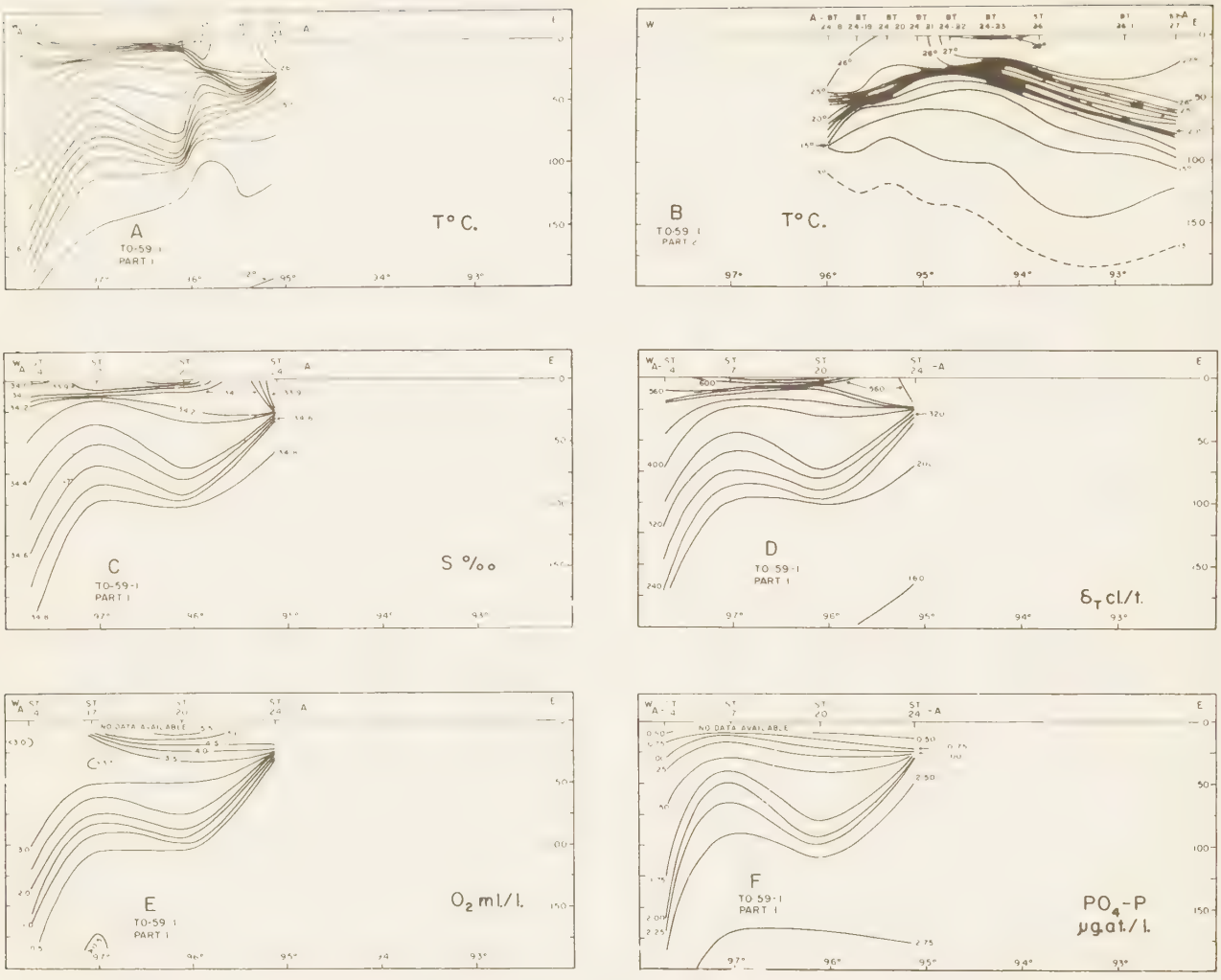


Figure 18.--Vertical distributions of properties on cruise TO-59-1, parts 1 and 2, along section A-A (see fig. 15); depth scale in m.

are comparable with those that prevailed in May and June on cruise TO-58-1.

Horizontal distributions of properties

Figure 21 is a set of charts of: (A) dynamic height anomaly and surface current, (B) surface temperature, (C) surface salinity, (D) phosphate at 30 m., and (E) zooplankton and micronekton. There is no chart for oxygen because surface conditions were uniform for this property, as noted on figure 21C.

Figure 21A shows a more meridional dynamic topography than was noted on other cruises. The crest of the ridge was between 95° and 94°, as in figures 4A and 10A. Surface current agreed reasonably well with geostrophic current except south of 14°.

Surface temperature was more uniform than on any previous survey (fig. 21B). The general location of the coldest area was the same as previously, centered at about 15° N., 95° W. Temperatures generally were still higher than the long-term average for the month.

Figure 21C indicates the extension of water of salinity >33.8‰ to the surface in part of the ridge region, through a surface layer of generally lower salinity in the northern and eastern parts of the Gulf which was probably a result of dilution by waters run off from the coast. There was a north-south ridging of the isopleths of phosphate along 95° W., but not reaching the head of the Gulf (fig. 21D). Standing crops of zooplankton (and probably, from the meagre evidence available, of micronekton) were lower than on any previous cruise, although for this cruise the highest

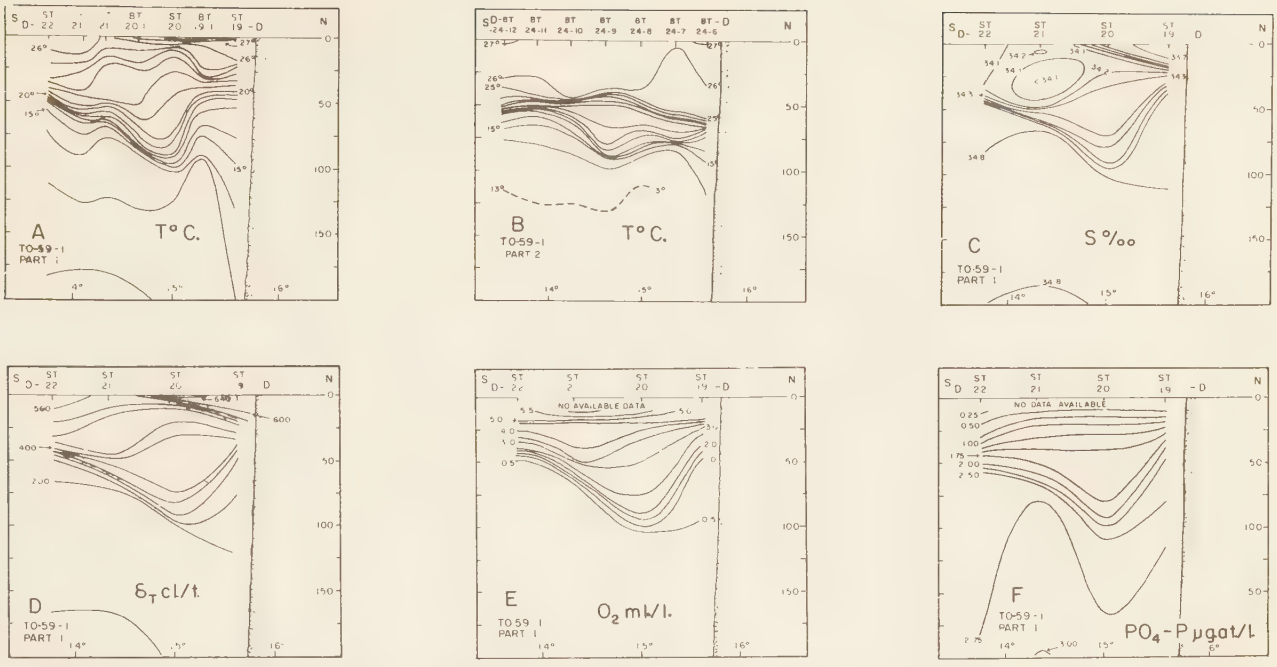


Figure 19.--Vertical distributions of properties on cruise TO-59-1, parts 1 and 2, along section D-D (see fig. 15); depth scale in m.

concentrations were still found in the ridge area and westward (fig. 21E). Standing crops of chlorophyll a were also lower than on any other cruise (fig. 5A); productivity values tended to be higher than on TO-58-1 (May and June), although much lower than on TO-58-2 (November) and TO-59-1 (January and February), as shown in figure 5B.

Vertical distributions of properties

Figure 22 presents profiles along the east-west section A-A of: (A) temperature, (B) salinity, (C) thermosteric anomaly, and (D) oxygen. There is no figure for phosphate because of a shortage of observations in the upper part of the column at station 78.

All these profiles show a discontinuity layer topography like that of all previous surveys but smoother than that found on most of them, most comparable with the situation on part 2 of TO-58-2 in November (fig. 11A). The top of the layer reaches to about 25 m. below the sea surface on the crest of the ridge; on meridian 97° the corresponding depth is about 40 m. The longitude of the crest of the ridge is further west than usual (95° instead of 94°), and there is upward extension of a few isopleths in this region and westward.

Figure 23 gives the corresponding profiles along the north-south section B-B. They show a comparatively small amount of vertical mixing of the upper part of the discontinuity layer and that confined, as in May and June on cruise TO-58-1 and in November on cruise TO-58-2 (part 3), to the mid-Gulf region at about latitude 15° N. There is a pronounced downward slope of isopleths to the coast, where the top of the discontinuity layer is perhaps too deep for wind-stirring to have occurred.

Interpretation

The circulation during this September survey resembled that of the right-hand schematic diagram in figure 2B (for May and September). There was no indication of either a western or an eastern eddy, and in general both the surface and the geostrophic current were weaker than on previous cruises. The topography of the discontinuity layer was consistent with the circulation, i.e., comparatively smooth. The locations of the main features of this topography, with respect to the coast and the direction of the predominant wind, were, nevertheless, much as on previous cruises. So was the location of the area of maximum destratification, although this

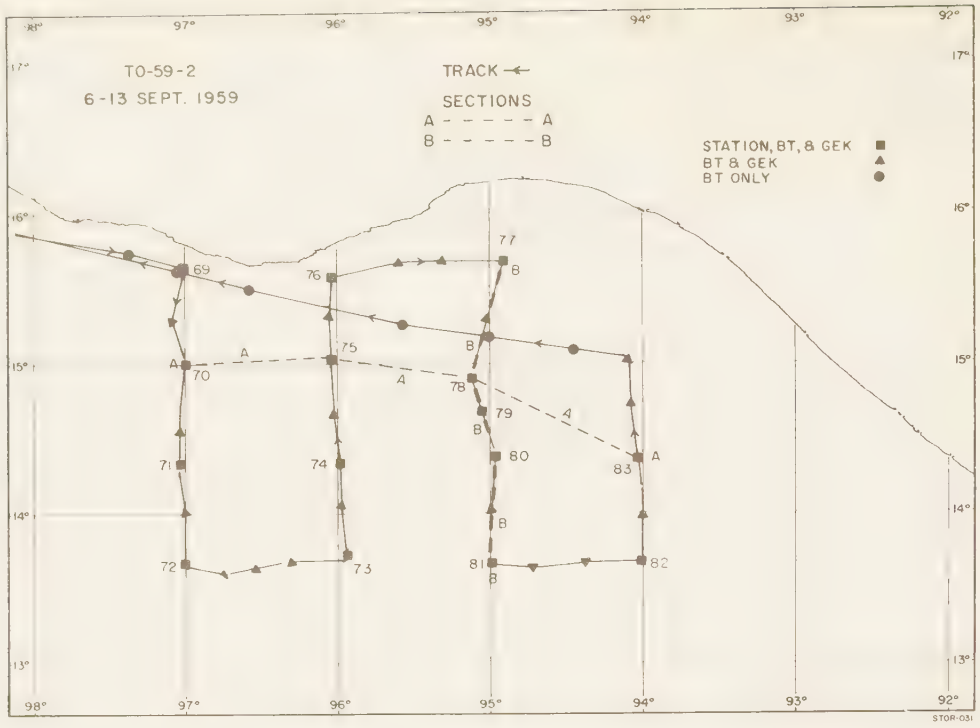


Figure 20.--Track chart of cruise TO-59-2 in the Gulf of Tehuantepec.

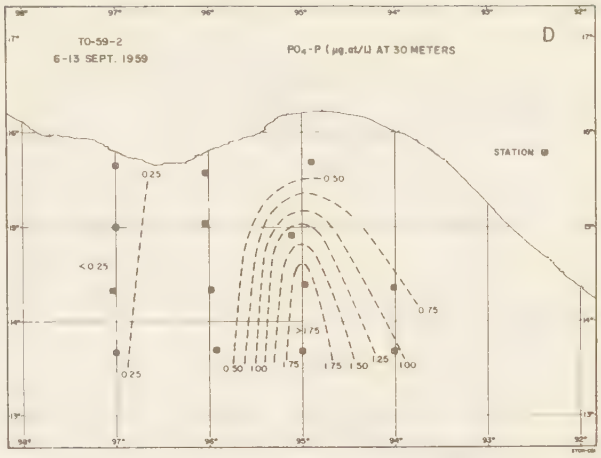
feature itself was less well marked than in any previous survey. Phosphate concentration in surface and near-surface waters was closer to that of TO-58-1 (May and June) than to that of the other cruises. The biological properties were lower than on other cruises, except productivity which appeared to be a little higher than it was on TO-58-1.

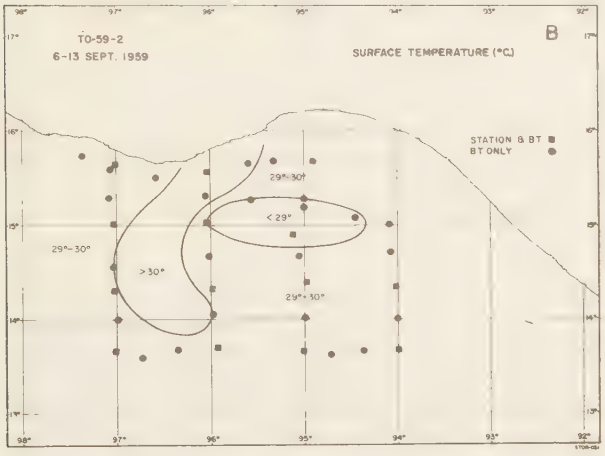
All these features would be expected for this region, from the average wind and current picture of figure 2 and the observations made on the previous cruises, at the transition from the calmer conditions of summer to the more disturbed conditions of the Tehuantepecer season. The ocean is highly stratified and its strata are more nearly parallel to the sea surface than at any other time of year (except possibly in midsummer when no observations were made); therefore, the processes (vertical mixing) resulting in production of biota are weakly developed and so are the processes (horizontal transport) resulting in redistribution of biota, and this weak development is reflected in the abundance and distribution of biological material.

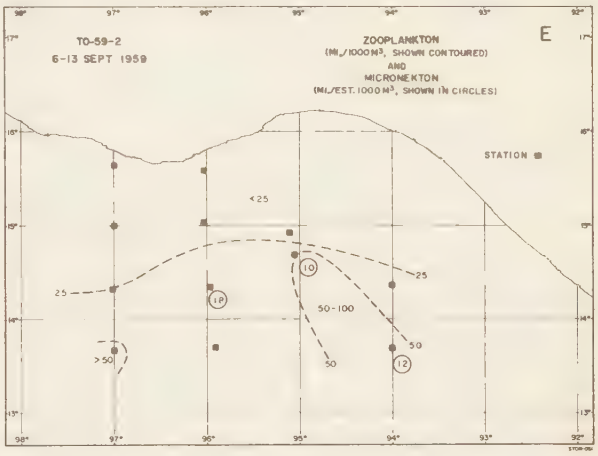
DISCUSSION

Most features of the data have been discussed in previous sections of the paper. This section comments further on a few of the most interesting features.

Brandhorst (1958) thought it remarkable that the area of lowest surface temperatures should lie west of instead of at the highest point of the feature he called a dome. Present observations on this point are consistent with his. It is easy to understand the phenomenon if it is considered that the south-moving wind stream acts first to produce a ridge on its left-hand side, and secondly to disturb the part of this ridge lying closest to its







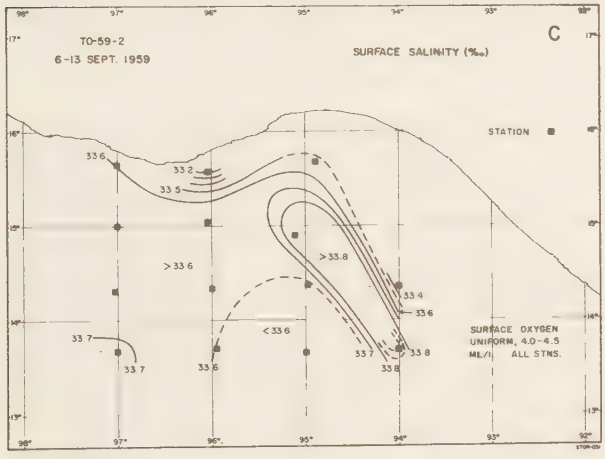


Figure 21.--Horizontal distributions of properties on cruise TO-59-2.

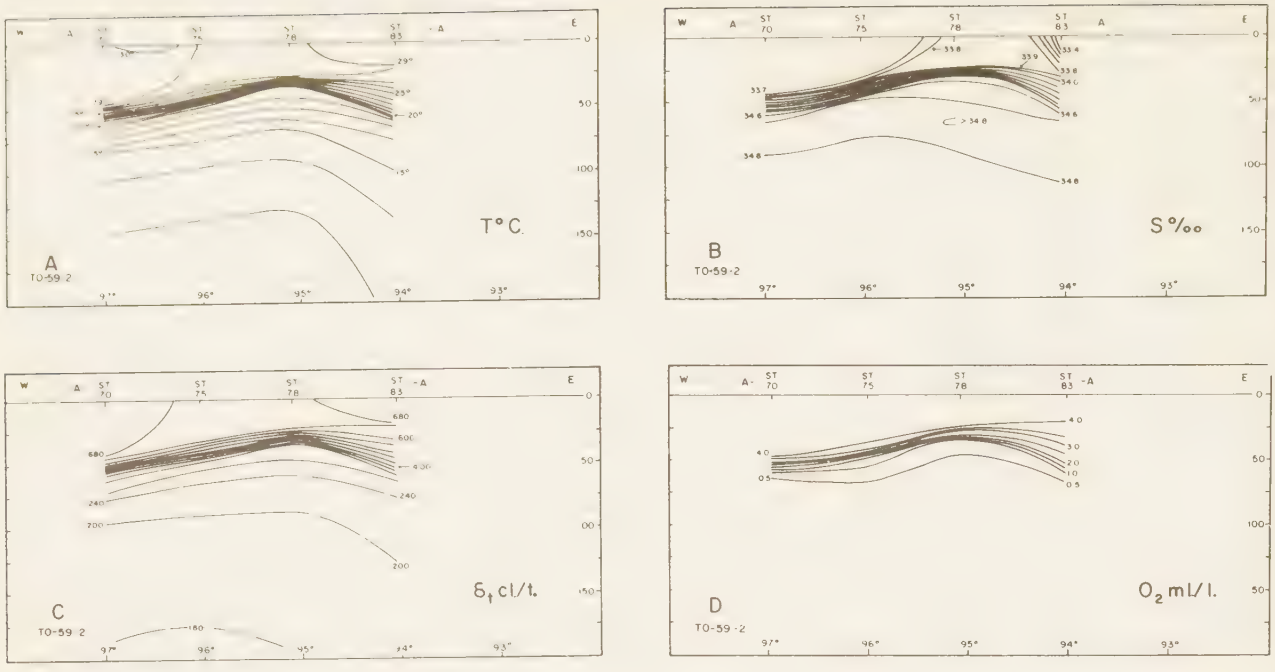


Figure 22.--Vertical distributions of properties on cruise TO-59-2, along section A-A (see fig. 20); depth scale in m.

path (i.e., the western flank or shoulder of the ridge).

This explains the longitude but not the latitude of the cold area: it does not explain why the coldest surface area usually lies in the offshore section of the wind's path instead of inshore, where wind stress is greatest (Roden 1961, see footnote 2). No explanation can be given with confidence. The one suggested in the section on TO-58-1 is that there is an additional cause of upward transfer of cool water, namely local divergence; there is some evidence that this might occur in the general area of the cold center, but no such evidence is available for part 3 of TO-58-2, when upward transfer was particularly noticeable. Another possibility, mentioned in the section on TO-59-2, is that the offshore cold center is the location of the highest point of the original topography and therefore more subject to wind-stirring than the more inshore waters, notwithstanding the greater wind stress in the inshore waters; this idea is suggested by figure 23A, and by Brandhorst's figure 9 which shows the thermocline top much closer to the surface at its highest point than in any figures in this paper, at an offshore station. Two other suggestions that have been made are: (a) the inshore cold area tends to be obliterated by entry of warm water from east or west, in the way suggested in "Previous oceanographic information"; and (b) the waves that accomplish much of the wind-stirring may be better developed offshore than inshore, because of greater fetch.

If the considerable destratification at station 11 in figure 12C could be ascribed to wind-induced divergence it would be correct to speak of it as upwelling (Cromwell, 1958; Austin, 1960). It cannot confidently be said that there is such divergence, in the above-mentioned situation or in any other described in this paper; moreover, most temperature profiles in the region of the cold center show a fairly well-developed thermocline: therefore all such situations are regarded as examples of "vertical mixing and stirring" in the sense of Cromwell (1958). It is possible, as mentioned in the interpretation of data for cruise TO-58-2, that some of the mixing was energized from sources other than wind.

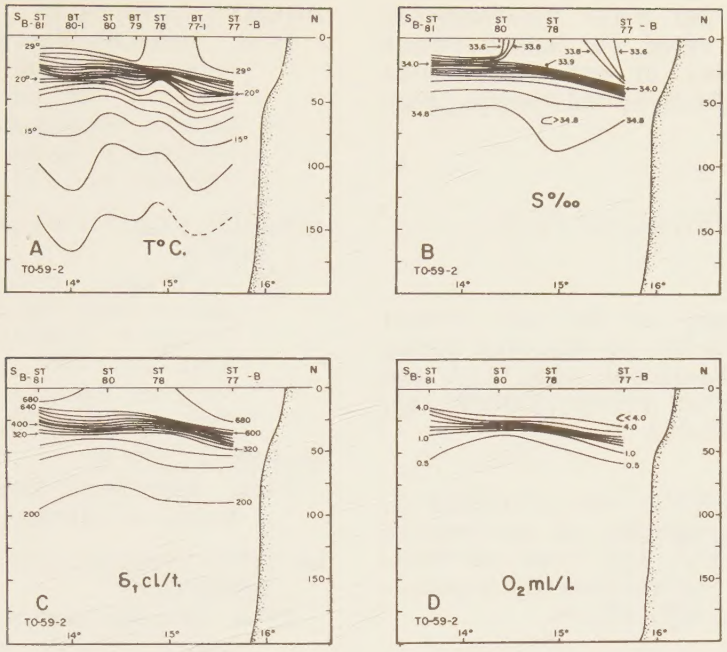


Figure 23.--Vertical distributions of properties on cruise TO-59-2, along section B-B (see fig. 20); depth scale in m.

SUMMARY

It is concluded, from information obtained on four cruises in 1958 and 1959 and data available in published average charts, that the prevailing transisthmian northerly wind affects the upper waters of the Gulf of Tehuantepec in the following ways in the period September through May (and possibly to a less extent during the remaining 3 months, although no observations have been made).

1. The prevailing northerly winds cause a current to flow from the head of the Gulf to the south and southwest. The effect of this, added to the effect of the normal flow northwestwards along the Mexican coast, is to produce in the Gulf a more or less permanent flow pattern like that of a letter S rotated 90° clockwise, with its axis lying east and west after rotation. As a result the discontinuity layer (pycnocline, thermocline, etc.) forms a meridional ridge in the eastern half of the Gulf and a hollow in the western half.

2. Stronger northerly winds (Tehuantepecers) increase the velocity of the southerly current and the slope of the western side of the ridge, and bring the top of the ridge closer to the sea surface. This process starts in October or November.

3. As the discontinuity layer approaches the windy sea surface, its top is stirred and mixed-layer temperature, salinity, phosphate concentration, etc. become locally more like those of the discontinuity layer. Production of biota, first phytoplankton and later zooplankton and micronekton, is stimulated in the near-surface waters. Surface productivity is up to 161 mg.C/$m.^3$/day. These phenomena are best developed in the region where the ridge top is most affected by the wind, i.e., along the western shoulder of the ridge. Within that meridional belt they tend to be best developed at about latitude 15° N. instead of close to the coast, for reasons that are not entirely understood.

4. The biota tend to be carried downstream from the area of maximum production. If a strong clockwise eddy forms to the west of the ridge the effect is probably to concentrate some of the biota in the eddy region, but otherwise the effect is probably to transport them through the southwest waters of the Gulf. In any event the main concentration of zooplankton standing crop (the most ubiquitous biological measurement) is regularly in the southern, southwestern, or western parts of the Gulf. This concentration reaches about 600 ml./1,000 $m.^3$.

5. Towards the end of the Tehuantepecer season (May) the ridge and hollow flatten out, upward transfer of water properties diminishes, and productivity and standing crops of biota all decline.

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